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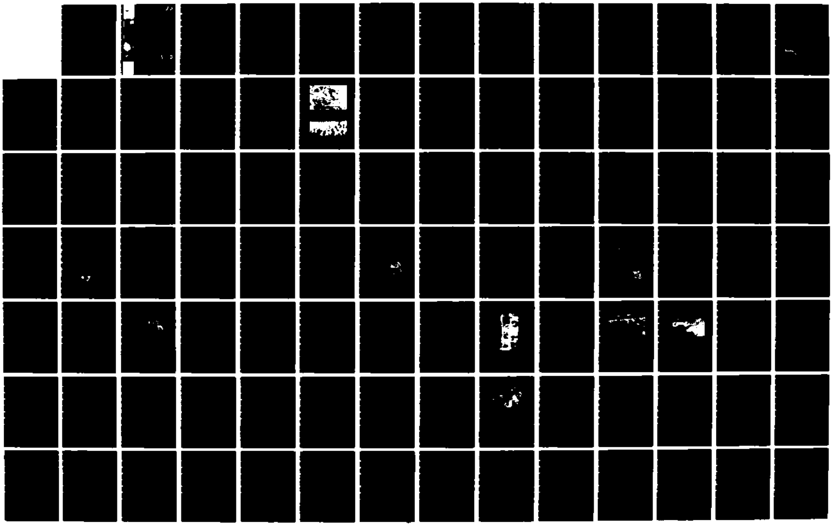

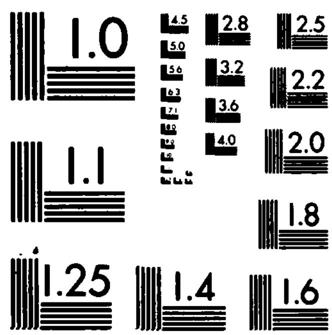

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THE ATCHAFALAYA RIVER DELTA

Report 4

GENERIC ANALYSIS OF DELTA DEVELOPMENT

by

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Coastal Studies Institute
Louisiana State University
Baton Rouge, La. 70803

January 1984
Report 4 of a Series

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Prepared for U. S. Army Engineer District, New Orleans
New Orleans, La. 70160

Under Contract No. DACW39-80-C-0082

Monitored by Hydraulics Laboratory
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report HL-82-15	2. GOVT ACCESSION NO. AD-A140446	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE ATCHAFALAYA RIVER DELTA; Report 4, GENERIC ANALYSIS OF DELTA DEVELOPMENT		5. TYPE OF REPORT & PERIOD COVERED Report 4 of a series 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John T. Wells Susan J. Chinburg James M. Coleman		8. CONTRACT OR GRANT NUMBER(s) DACW39-80-C-0082
9. PERFORMING ORGANIZATION NAME AND ADDRESS Coastal Studies Institute Louisiana State University Baton Rouge, La. 70803		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Engineer District, New Orleans P. O. Box 60267 New Orleans, La. 70160		12. REPORT DATE January 1984 13. NUMBER OF PAGES 101
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) U. S. Army Engineer Waterways Experiment Station Hydraulics Laboratory P. O. Box 631, Vicksburg, Miss. 39180		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Alluvial plains (LC)
Atchafalaya River--Delta (LC)
Deltas (LC)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The development of two freshwater deltas in Atchafalaya Bay is providing new subaerial land in south-central Louisiana in an area traditionally subjected to coastal retreat. From the engineering and scientific standpoints, it is important to know at what rate and by what mechanisms the deltas in Atchafalaya Bay will continue to grow. Utilizing maps, charts, aerial photographs, and published and unpublished literature, growth patterns in 10 similar deltas and
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20. ABSTRACT (Continued).

subdeltas were examined as a means of projecting the rate of growth and configuration of subaerial land in Atchafalaya Bay to the year 2030.

Results indicate that total subaerial land in Atchafalaya Bay will range from 150 km^2 to 337 km^2 with 208 km^2 representing the expected land in 50 years under average flood regimes. Subaerial land will emerge on the open shelf before the bay reaches a sediment-filled state. Persistent scour channels, slow sedimentation in distal areas, reworking of sediments during passage of cold fronts, subsidence, and selective natural sealing of the sediment delivery network will ensure that large areas of the bay will always remain open. The subaerial deltas will continue to grow as lobate additions of land caused by the processes of channel extension, channel bifurcation, and lobe fusion. Within 50 years the hundreds of small lobes will have fused into perhaps 10 major lobes separated by small dying channels.

Approximately 14×10^6 m^3 of sediment per year is retained in Atchafalaya Bay. Subaerial land that is lost during years of low river discharge resides in the shallow subaqueous environment and provides a platform for future subaerial growth. As the deltas prograde onto the shelf, waves and wind-driven currents will become more important in shaping the delta lobes. Strong southeasterly currents following the passage of cold fronts will tend to skew the sandy components to the southeast, thus fractionating them from the silts and clays that will be carried west in the predominant coastal drift system.

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PREFACE

This report presents results of a generic analysis of the two new deltas in Atchafalaya Bay, Louisiana. The study was supported as a reimbursable project within the Estuaries Division, Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for the U. S. Army Engineer District, New Orleans (LMN), Louisiana. Work was performed under Contract No. DACW39-80-C-0082 between WES and Louisiana State University, Baton Rouge.

The study was conducted under the direction of the following WES personnel: Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory; F. A. Herrmann, Jr., Assistant Chief of the Hydraulics Laboratory; R. A. Sager, Chief of the Estuaries Division; W. H. McAnally, Jr., Project Manager; and J. V. Letter, Jr., Contracting Officer's Representative.

We gratefully acknowledge the contributions of the following individuals at Louisiana State University: Mr. I. Ll. van Heerden, for providing us with data on the Wax Lake Delta and for assistance in determining the future configuration of the Atchafalaya River deltas; Dr. L. J. Rouse, Jr., for aid in LANDSAT analysis and in performing the cubic regression analysis; Mr. R. H. W. Cunningham, for supplying us with tide records, satellite imagery, and aerial photography; Mr. R. H. Baumann, for providing results on the computation of sediment volume in Atchafalaya Bay; Ms. J. Nelson, for her assistance in acquiring old maps and charts of the Mississippi River Delta; and Ms. A. F. Dunn, for her careful drafting of the figures.

We are also indebted to Mr. C. Knox, Mississippi River Commission, Vicksburg, Mississippi, for assistance in using files of historic maps and charts; Mr. J. Cooper, National Coastal Ecosystems Team, Slidell, Louisiana, for assistance in obtaining pertinent literature; Ms. D. McConnell, Louisiana Department of Transportation, Baton Rouge, for obtaining maps and charts of Louisiana and Texas; Dr. N. H. Hyne, University of Tulsa, Oklahoma, for providing maps of the Catatumbo Delta; the National Cartographic Information Center, NSTL, Mississippi, for aid in identifying and obtaining maps and LANDSAT images of Louisiana and Texas; and the Planning Division, LMN, for use of aerial photographs and surveys of the Mississippi River Delta.

Commander and Director of WES during the study and the preparation and publication of this report was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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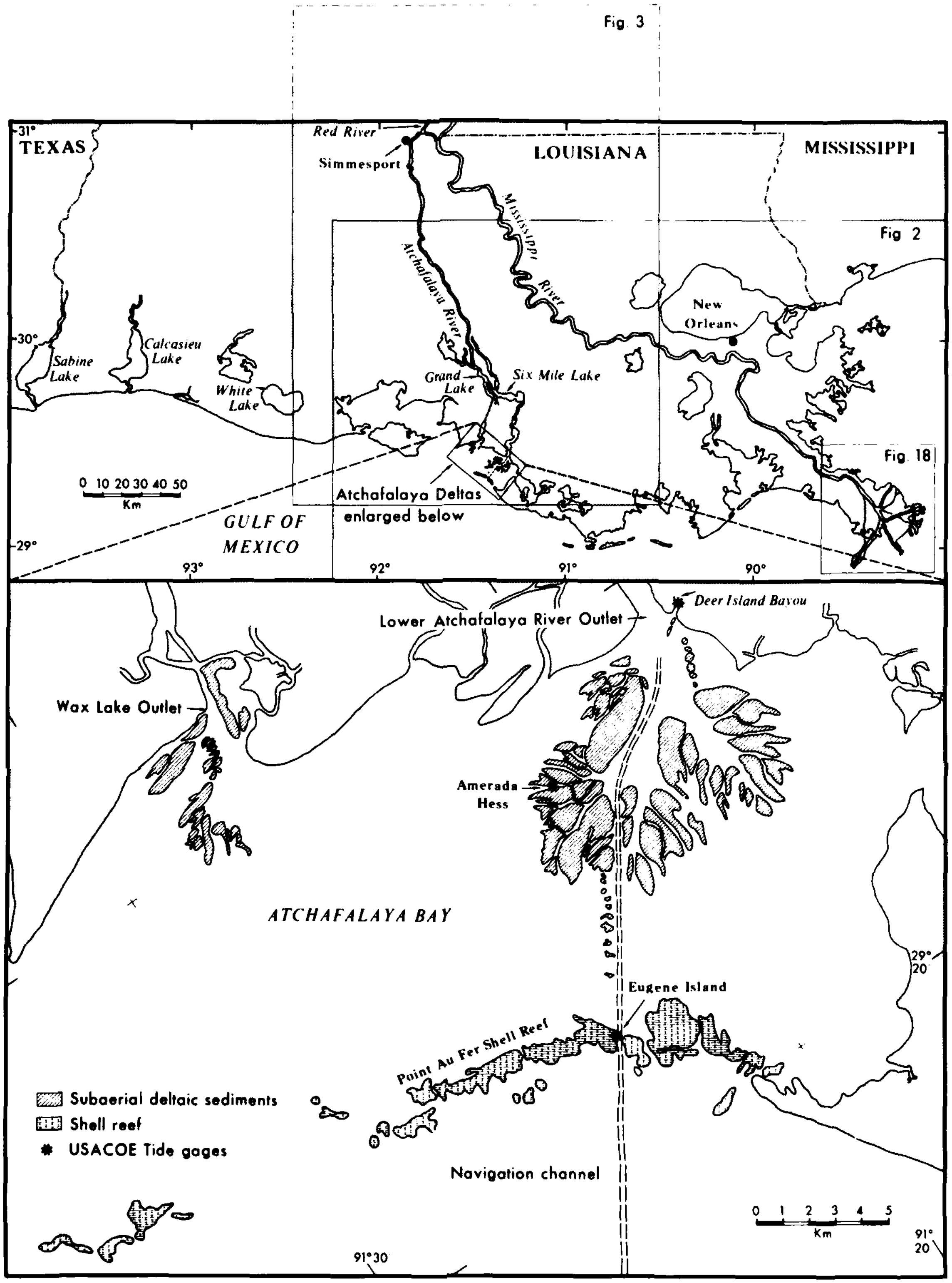

Figure 1. Index map of south Louisiana showing the location of the Old River diversion point, the Atchafalaya Basin and Bay, and the modern Mississippi River Delta. Enlargement of Atchafalaya Bay shows the two new deltas and locations of tide gages used in the LANDSAT analysis

THE ATCHAFALAYA RIVER DELTA

GENERIC ANALYSIS OF DELTA DEVELOPMENT

PART I: INTRODUCTION

Background

1. In Atchafalaya Bay of south-central Louisiana, a distributary of the modern Mississippi River is creating two new freshwater deltas of significant proportions (Figure 1). The most recent and dramatic phase of delta growth began in 1973, when the Lower Atchafalaya River Delta emerged subaerially and became partially vegetated. The rapid and, at times, unexpected progradation of this new delta brought with it both controversy and uncertainty as to the future of Atchafalaya Bay. By 1976 a second, smaller delta, the Wax Lake Delta, had become well established subaerially, following a growth pattern similar to that of the Lower Atchafalaya River Delta. The primary benefits from these two deltas have been the addition of new land to the coast of Louisiana in areas traditionally subjected to coastal retreat, natural creation of new marshes for marine habitation and for recreational purposes, and the initial stabilization of downdrift shorelines to the west. The most serious liabilities have been unwanted siltation in navigation channels and backwater flooding in the surrounding low-lying coastal parishes of South Louisiana.

2. The complexity of problems and processes associated with the new Atchafalaya River deltas, together with our lack of knowledge of incipient stages of delta growth, have given impetus for numerous Federal agencies to become involved in the study of physical and biological processes in Atchafalaya Bay and vicinity. As part of a multidisciplinary study undertaken by one of these agencies, the U. S. Army Engineer Waterways Experiment Station (WES), a "generic analysis" of delta growth was conducted in order to answer several key questions concerning development of the Atchafalaya River deltas.

3. From engineering as well as scientific standpoints, perhaps the most important of these questions is concerned with future evolutionary trends in Atchafalaya Bay. At what rate and by what means will

the deltas in Atchafalaya Bay continue to grow? The generic analysis was designed to aid in answering this important question by focusing on four specific objectives:

a. Project the rate of growth from the present to a future of 50 years on the basis of growth rates of similar deltas.

b. Construct a family of curves that would allow determination, from land area, volume, or contour advancement, approximately where the Atchafalaya River deltas are in their natural evolution.

c. Determine details of the growth process, such as rate of bifurcation and the extent to which an intricate pattern of small distributaries will develop.

d. Produce a map showing the configuration and extent of subaerial deltaic sediments projected to the year 2030.

4. The approach taken in the generic analysis has been to examine growth, and in many cases deterioration, of deltas and subdeltas throughout the world that appear to be similar to the deltas in Atchafalaya Bay. Ten deltas in three geographic "categories" were selected for analysis: Mississippi River subdeltas (Baptiste Collette, Cubits Gap, West Bay, and Garden Island Bay); East Texas deltas (Trinity, Colorado, and Guadalupe); and deltas outside the U.S. (the Danube in Romania, Laitaure in Sweden, and Catatumbo in Venezuela). By quantifying the growth process in each of these carefully selected deltas, it was anticipated that much of the speculation concerning future trends could be removed.

5. The data base consisted primarily of maps, charts, and LANDSAT imagery, but also included survey sheets, aerial photographs, dredging records, and published and unpublished accounts of delta growth. Each map, chart, and image was traced, scaled, and digitized, then archived for future reference. Using these data, this report documents in the following paragraphs the (a) early history of Atchafalaya River and its deltas, (b) evolutionary trends of 10 similar deltas and subdeltas from other regions, (c) detailed trends in Atchafalaya delta growth since subaerial emergence in 1973, (d) projected growth rates and patterns in Atchafalaya Bay and offshore to a future of 50 years, and (e) rationale used in projecting the location of subaerial land and its future configuration.

6. Evolution of the modern Atchafalaya River is an example of the periodic diversion and potential capture of main stream flow by a distributary. The process of channel switching or diversion in the Mississippi River is a natural one that over the past 6000-8000 years has resulted in the deposition of seven major delta complexes (Figure 2; Kolb and Van Lopik 1958) that are sometimes further divided into 16 separate delta lobes (Frazier 1967). Each major delta complex of the Mississippi River system remained as an active depositional site for approximately 1000 years. When progradation reached the point at which any gradient advantage was lost or when the river could no longer efficiently handle the water and sediment discharge, the delta commenced its abandonment stage and a new route to the sea was established by the river. The modern bird-foot delta, referred to as the Balize Delta, commenced development approximately 800 years ago; already it has attempted to relocate its site of deposition via a change in course to the Atchafalaya River, a route to the sea that is some 307 km shorter (Roberts, Adams, and Cunningham 1980).

7. Three of the previous seven delta complexes, the Sale Cypremort, Teche, and Lafourche, covered the Atchafalaya Bay and vicinity with perhaps 25 m of alluvial-deltaic sediments, which form the base for present-day Atchafalaya River sedimentation (Kolb and Van Lopik 1958). These Holocene sediments of the Atchafalaya Bay are underlain by the Pleistocene Prairie Formation, a young regressive Pleistocene-age sedimentary unit that consists of normally consolidated, oxidized, clay-sized sediments deposited when sea level was below its present elevation. The Pleistocene Prairie Formation in Atchafalaya Bay has been downwarped approximately 30 m in Quaternary time as a result of regional subsidence associated with the Gulf Coast Geosyncline (Fisk and McFarlan 1955). With the eastward shift in sedimentation to the Balize Delta 800 years ago, the south-central Louisiana coast received its last input of Mississippi River Delta sediments until the early 1900's.

8. During 400 of the last 800 years, a well-defined sequence of events set the stage for future deltaic sedimentation in Atchafalaya

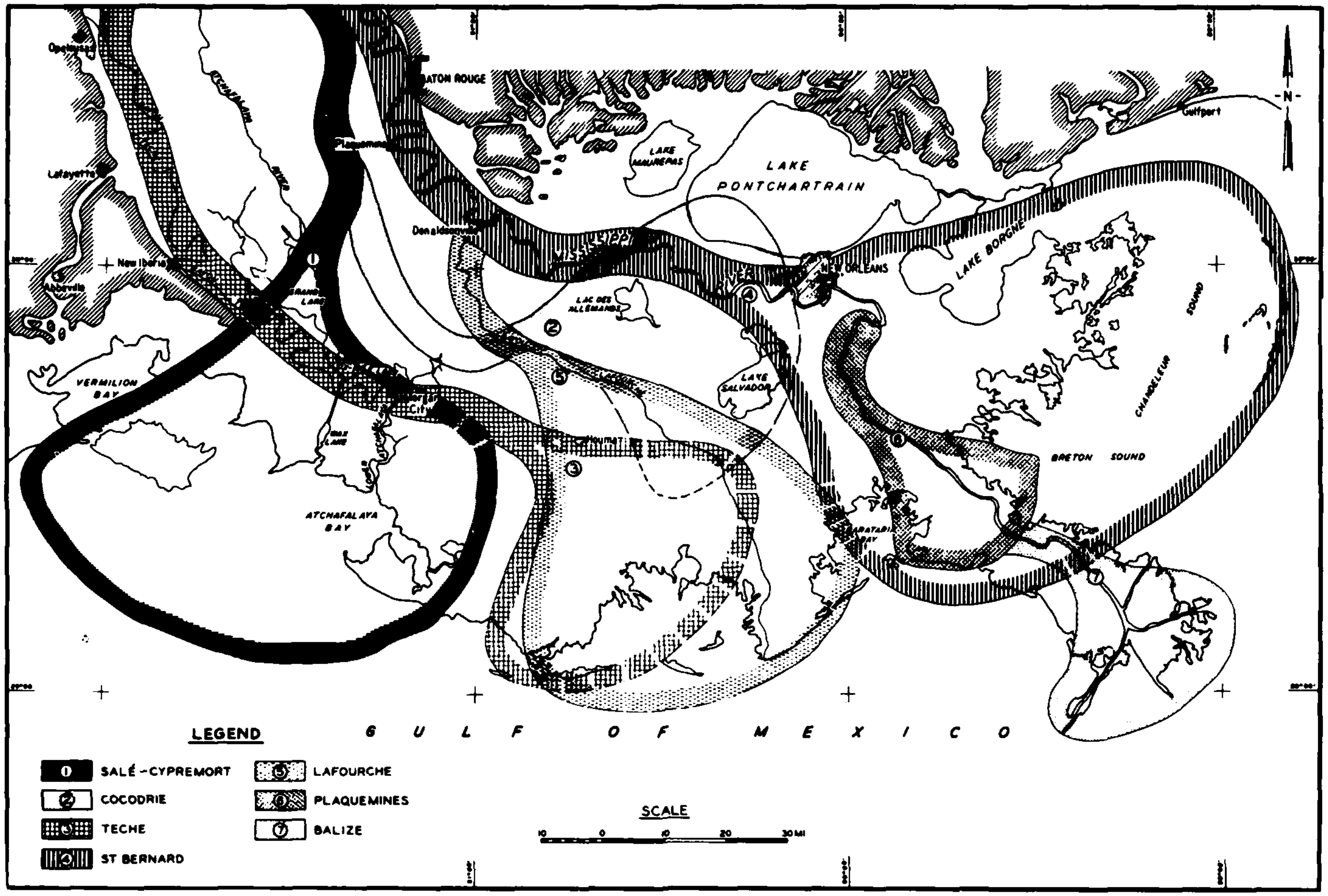

Figure 2. Location and relative size of the seven major delta complexes that have been active in southeast Louisiana during the last 6000-8000 years (from Kolb and Van Lopik 1958)

Bay. According to Fisk (1952), the Atchafalaya River was a definite distributary of the Mississippi River by 1542, flowing through a broad interdistributary basin between the older Teche course to the west and the modern Lafourche course of the Mississippi River to the east (Figure 3). Log jams were first cleared in 1839, and during the mid- to late 1800's limited flow from the Mississippi River was maintained by continual dredging. By 1940, sufficient flow had been diverted from the Mississippi River to allow a natural channel to become established. Aided by dredging, the volume of flow to the Atchafalaya River from the Mississippi River increased steadily from 13 percent in 1900 to nearly 30 percent in 1952 (Morgan, Van Lopik, and Nichols 1953).

9. Until 1952, deltaic sedimentation during the last four centuries had been confined almost exclusively to the lakes and swamps of the Atchafalaya Basin. Cratsley (1975) reported that insignificant sedimentation, as indicated by bathymetric data, occurred in Atchafalaya Bay between 1858 and 1952. Sediments that escaped the catchment basins to the north bypassed Atchafalaya Bay and were deposited on the inner shelf. Shlemon (1975) states that approximately 2 m of clay was deposited seaward of the Point au Fer shell reef between 1889 and 1935 and another metre by 1951. Two explanations have been offered for this apparent bypassing of the bay. Morgan, Van Lopik, and Nichols (1953) indicated that suspended clays transported down the Atchafalaya River flocculated upon reaching the saline waters seaward of Atchafalaya Bay, thus forming a blanket of prodelta clays on the shelf alone. In addition to flocculation, Thompson (1955) used the concept of "equilibrium depth," a depth maintained by nonhurricane wave action, as a means of explaining the lack of permanent sedimentation in the bay.

10. The trapping of deltaic sediments, primarily in Grand and Six-Mile Lakes (Figure 1), resulted in extensive lacustrine delta-fill deposits over a 50-year period. Between 1917 and 1960, Grand and Six-Mile Lakes served as an active trap for coarser sediments destined for Atchafalaya Bay. By 1975, only small remnants of these lakes remained as open water (Roberts, Adams, and Cunningham 1980). The final approach to a sediment-filled state by the mid-1900's allowed prodelta clays to begin

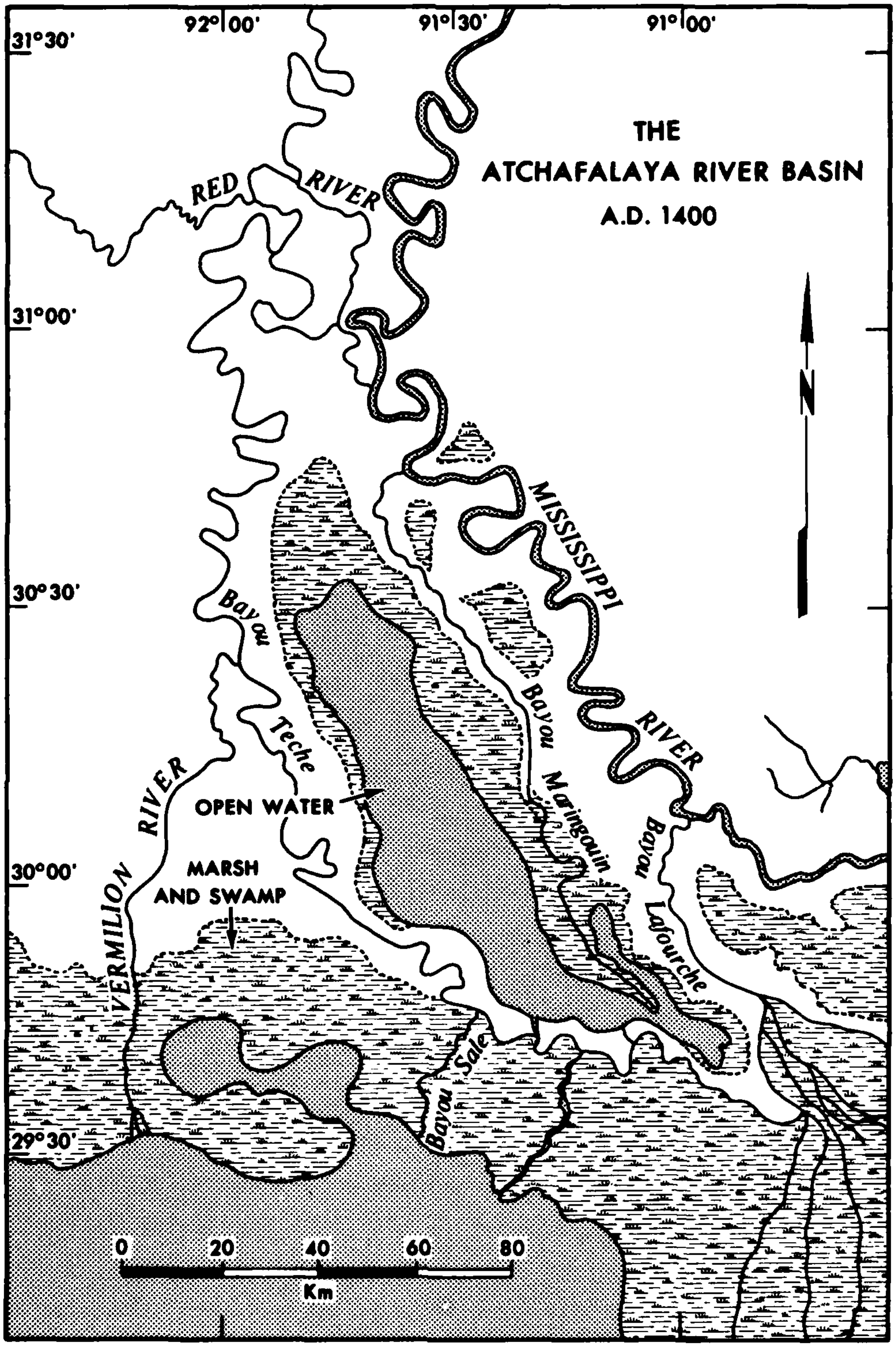

Figure 3. The Atchafalaya River Basin in 1400 A.D. showing locations of Bayous Teche, Maringouin, and Lafourche (from Fisk 1952)

accumulating in Atchafalaya Bay. The decade 1952-1962 marks the beginning of a subaqueous delta at the mouth of the Lower Atchafalaya River Outlet.

11. By 1962, 0.3 m of fine-grained sediment covered 120 km^2 of the Bay (Shlemon 1975). Although sedimentation at the Wax Lake Outlet, artificially opened in 1942, was small compared with that at the Lower Atchafalaya River Outlet, the Wax Lake Outlet carried a full 30 percent of Atchafalaya River flow. Growing concern over possible abandonment of the Mississippi River in favor of the Atchafalaya River, predicted to occur by 1975 (Fisk 1952), led to the completion of a control structure in 1963 at the Old River-Mississippi River juncture. Diversion of Mississippi River flow down the Atchafalaya River was limited to approximately 30 percent of the combined flow from the Mississippi and Red Rivers (Figure 1).

12. A period of delta-front or distal-bar sedimentation (subaqueous delta deposits) occurred between 1962 and 1972, marked by the first introduction of silts and fine sands to the bay. An isopach map from Shlemon (1975) showed 285 km^2 of the bay covered by clay, silt, and fine-grained sand, as well as the first appearance of distributary channels. The thickest accumulations of sediment were west of the Lower Atchafalaya River and Wax Lake Outlets, reflecting partly the position of submarine spoil banks. Also during the period of distal-bar sedimentation prior to 1972, the first series of scour channels formed just inside the Point au Fer shell reef.

13. By 1972, 1.8 m of fill had been deposited in the delta lobes of the Lower Atchafalaya River and Wax Lake Outlets, and the submarine delta front had advanced to the Point au Fer shell reef (van Heerden 1980). The spring flood of 1973, one of the largest on record, produced the first natural subaerial expression on both the east and the west sides of the Lower Atchafalaya River navigation channel. Rapid growth over the next 3 years, when referenced to mean low water, resulted in 32.5 km^2 of new land in the Lower Atchafalaya River Delta (Rouse, Roberts, and Cunningham 1978) and 3.8 km^2 of new land in the Wax Lake Delta (van Heerden 1980).

14. A series of cores through the Lower Atchafalaya River Delta

(van Heerden, Wells, and Roberts 1981) reveals that basal prodelta clays have broad lateral continuity and little textural variation. Shlemon (1972) indicates that on average they are 0.6-0.9 m thick. Overlying the prodelta facies is the coarsening-upward sequence of distal-bar sediments deposited from 1962 to 1972. Close to the distributary mouths, the distal-bar sediments become transitional to a shallower, sand-rich distributary-mouth-bar facies, deposited rapidly as flow becomes unconfined at the seaward end of each distributary. As a generalization, progradation of the deltas in Atchafalaya Bay leads to deposition of coarser sediment over a base of finer sediment, with strong modulation from river discharge, tidal currents, wave action, and wind-driven currents.

15. A detailed examination of hydrologic regime and sediment flux in the Atchafalaya Basin and Bay revealed two important characteristics (Roberts, Adams, and Cunningham 1980): (a) a change in dominance of sediment entering the bay during the last 20 years from silt and clay to silt and fine sand, and (b) abnormally high discharge during the years of initial subaerial growth, 1973-1975. The increase in sand that reached the bay can be attributed to scour of previously deposited channel, levee, and lake-fill sediments, as well as an increase in net passage of sand through the basin. An increase in average annual sediment load from 42.6 million metric tons (1965-1971) to 88.9 million metric tons (1973-1975) likewise reflects the effects of both scour within the basin and a larger input above the diversion point near Simmesport, Louisiana, during major floods. Average annual water discharge at Simmesport is 5,126 m^3/sec (USAED, New Orleans, 1974), and average annual peak flow is 12,121 m^3/sec (Figure 4).

16. The subaerial part of the Lower Atchafalaya River Delta today is highly vegetated during 8 months of the year and displays distinct morphologic lobes that are surrounded by a network of small bifurcating channels (Figure 5). Elevation of the sand-rich subaerial delta ranges from near mean sea level on newly emergent lobes to 2.8 m on large spoil banks; channel depths, exclusive of navigation channel, range from 1 to 3 m.

PART II. DATA ACQUISITION AND METHODS OF ANALYSIS

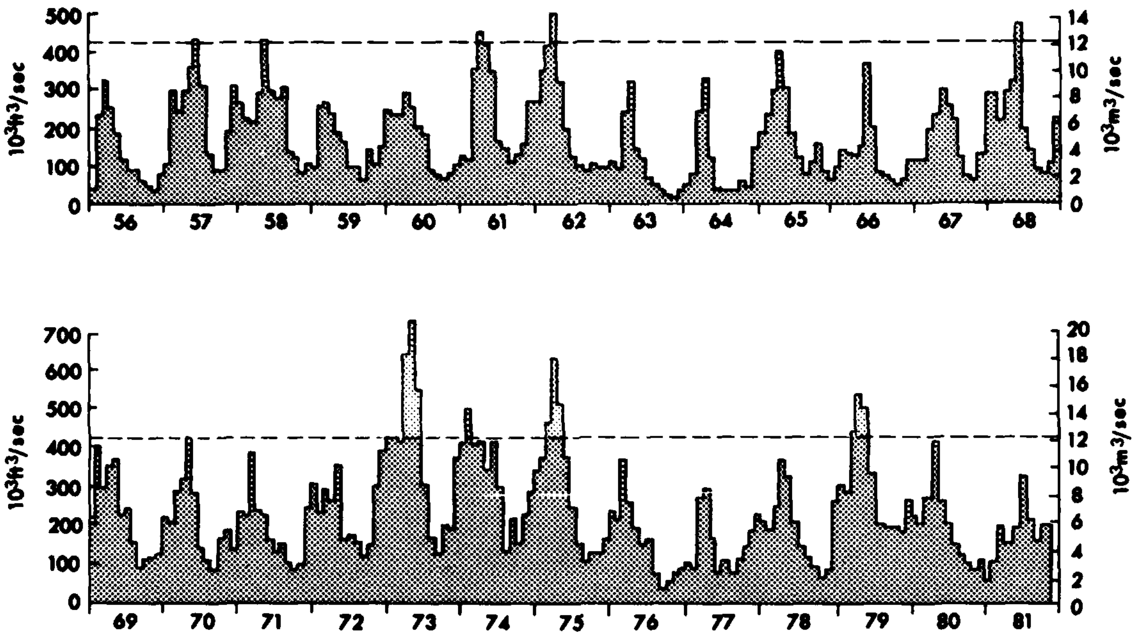

Figure 4. Average monthly discharge of Atchafalaya River at Simmesport. Dashed line represents average peak flow of 12,121 m^3/sec (modified from Roberts, Adams, and Cunningham 1980)

17. The first step in the generic analysis was to define a data base by selecting deltas from around the world that closely resembled the Lower Atchafalaya River Delta both in form and in setting. As a generalization, the requirements were low wave and tide energy, shallow receiving basin, and high suspended-sediment load. Final selection was made using the eight "process variables" given by Coleman and Wright (1975): climate, river discharge, sediment type, wave power, tide range, alongshore currents, shelf slope, and tectonics. Since these eight variables control the morphologic development of a delta, one can reasonably expect that similar fluvial and marine processes should produce similar growth histories. No attempt has been made to rank these process variables according to importance.

18. Ten deltas from three geographic categories and five environmental settings were selected for analysis: four subdeltas of the modern Mississippi Delta in a humid subtropical setting (Baptiste Collette, Cubits Gap, West Bay, and Garden Island Bay); three East Texas deltas

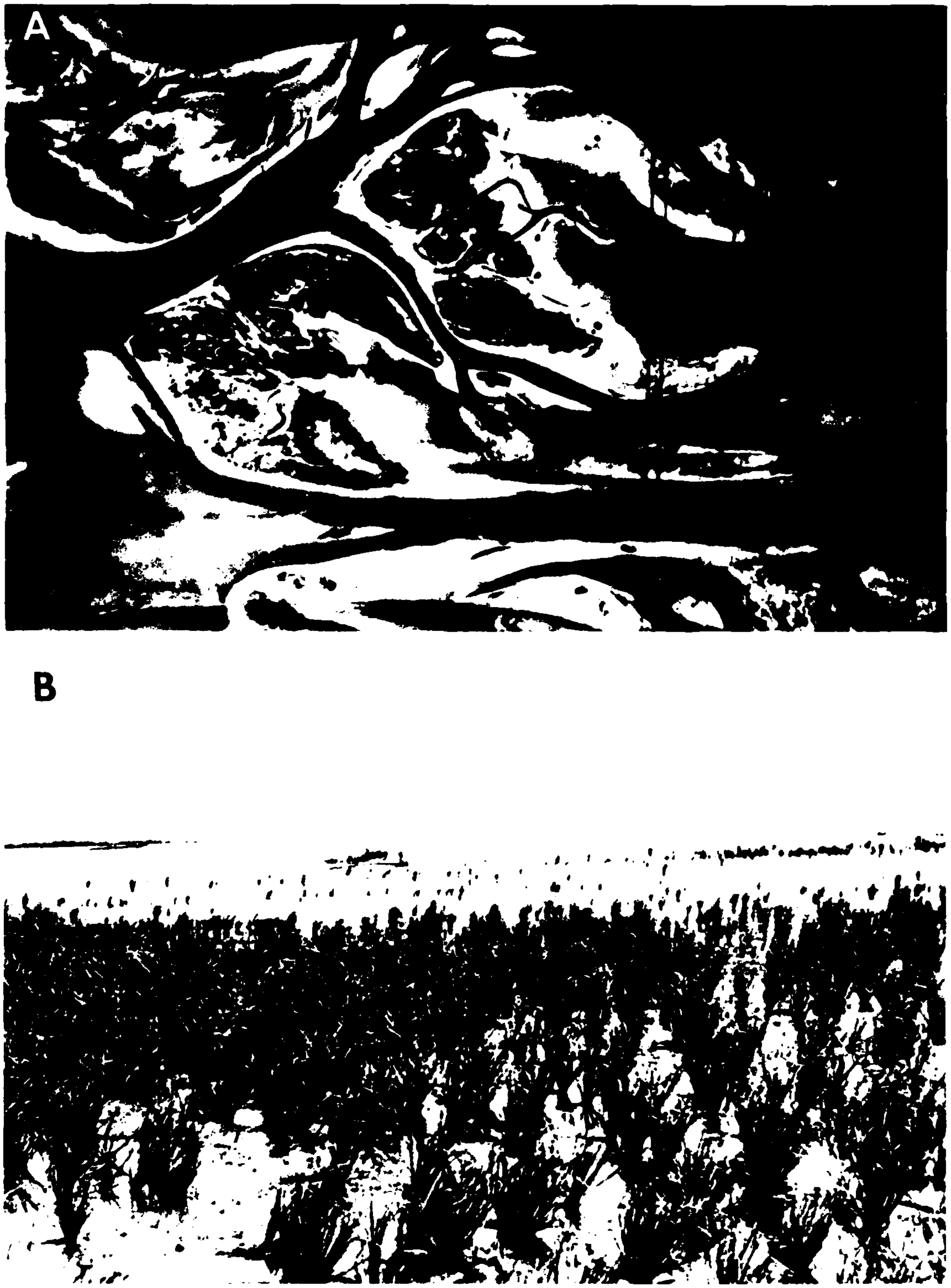

Figure 5. Parabolic delta lobes in Lower Atchafalaya River Delta as seen from the air (A) and emergent vegetation as seen from the ground on a sandy delta lobe (B)

in a humid to dry subtropical setting (Trinity, Colorado, and Guadalupe); and three deltas outside the U.S. in a glacial lacustrine (Lake Laitaure), tropical lacustrine (Lake Maracaibo), and temperate marine (Danube) setting. Table 1 provides, where possible, a quantification of the eight process variables for each delta or subdelta. Table 2 gives for each process variable a rating of similarity to the Lower Atchafalaya River Delta.

19. The task of determining similarity to the Atchafalaya River deltas is difficult and must be approached somewhat subjectively for two reasons. First, some of the process variables, such as tectonics, have not been accurately quantified. Whereas tide range and shelf slope can be readily measured, tectonic stability, including the effects of local subsidence and regional sea-level rise, are highly variable and poorly understood. Second, a strict quantitative comparison of some variables, such as river discharge, can be misleading. Whereas a river may have an average sediment discharge equal to that of the Atchafalaya River, that same river may carry 90 percent of its sediment during one catastrophic 2-week period each year. Moreover, many dams have been constructed during the life of the deltas under consideration, thus changing the sediment discharge substantially during growth.

20. The evaluations of process-variable similarity given in Table 2, if averaged for each delta or subdelta, indicate that the Baptiste Collette, Colorado, and Guadalupe Deltas are most similar to the Lower Atchafalaya River Delta. However, similarity alone does not ensure the usefulness of a particular delta, since one of the major constraints in the generic analysis was the lack of historic data. Thus the second step in the generic analysis was to identify, locate, and acquire historic information on the deltas and subdeltas selected for analysis.

21. A search was initiated to collect maps, charts, and published literature on each delta, then expanded to include aerial photographs, LANDSAT images, survey sheets, dredging reports, and unpublished data. By far the largest number of historical maps and charts was found for the Mississippi subdeltas; these were also considered to be the most accurate. The map library at the Louisiana State University Department

of Geosciences was able to provide most of the maps and charts for the Mississippi subdeltas and some of those required for the East Texas deltas. Other sources of data were the Mississippi River Commission, Vicksburg, Mississippi; U.S. Army Engineer District, New Orleans, National Cartographic Information Centers, NSTL, Mississippi, and Reston, Virginia; and National Ocean Survey, Rockville, Maryland. Maps for the Laitaure and Danube Deltas were obtained as supplements to published and unpublished reports; maps for the Catatumbo Delta in Lake Maracaibo were acquired on loan from the University of Tulsa (courtesy of Dr. Norman Hyne).

22. The initial search revealed surprisingly few surveys of the deltas, yet produced hundreds of maps and charts that varied tremendously in quality. For example, the 300 or so maps and charts that exist for the Mississippi Delta were based on fewer than 20 different surveys. Between the 1830's and early 1900's the U.S. Coast and Geodetic Survey compiled detailed and comprehensive surveys that were subsequently used by many other map-making agencies. Further, the dates on many early charts do not indicate dates of survey, but simply dates of printing. An early screening process was used to remove maps that were suspect and those that were duplicated from a single survey. In total, approximately 400 maps and charts were examined, 150 were copied or purchased, and 40 were used in constructing the growth curves (Appendix A). An extensive listing of maps and charts for the coast of Louisiana can be found in Morgan and Wright (1955) and Morgan (1977).

23. The third step in the generic analysis was to digitize subaerial land in order to determine total area for a given survey. The process of digitizing involved following the land-water boundaries using a cursor attached to a mechanical arm on a digitizing table. Prior to digitizing, it was necessary to select boundaries for the deltas or subdeltas that included all areas subjected to sedimentation. Although the process of digitizing did not require each map to be at the same scale, it was necesary to construct the boundaries on each delta in precisely the same fashion.

24. Each map to be digitized was fastened to a platen, scaled

by measuring on the map several known ground distances, and traced with the cursor of a Nova 1220 digitizer. Linear variations of 0.025 mm (~0.001 in.) could be resolved, corresponding to a ground distance of 1.25 m when using a 1:50,000-scale map. This resolution is considerably less than the error introduced artificially by unsteady hand movements and is more precise than the significance of the data warrants. As subaerial land is traced, the digitizer computes area from numerical coordinates using euclidian distance and trapezoidal integration. For complex areas with hundreds of small lobes, such as the Mississippi subdeltas during their deterioration, subaerial land can be traced from one small lobe to another without lifting the cursor. Total area is then read directly from the digitizer. On the other hand, larger delta lobes can be treated individually by reporting each of their areas and summing them to acquire the total amount of subaerial land.

25. The volume of deltaic sediments was computed using a conventional contour-area method (Brinker 1968). Only those deltas with sufficient bathymetric data collected at the time of the subaerial survey could be used. Thus one of the difficulties was that bathymetric surveys were not updated each decade, as the subaerial surveys were (less frequently in the East Texas deltas). The number of data points was therefore less than that for subaerial growth, but usually on the order of three to six. Three assumptions were required for the computation of volume. First, the depth of the receiving basin prior to a crevasse break or to obvious infilling was assumed to be the base of deltaic sedimentation. Second, it was assumed that the receiving basin was completely filled with sediment from its base up to a depth of 1.83 m (6 ft), i.e., no channels had depths greater than 1.83 m. Overestimates in volume using the assumption of complete infilling were probably balanced by the third assumption, which excluded the volume of sediment that may have been above mean sea level (0-m contour).

26. Determinations of volume were calculated from Equation 1:

$$V = \frac{(A_b + A_6)(D - 6)}{2} + \frac{(A_6 + A_o)\,6}{2} - V_p \qquad (1)$$

where A_b = area of base (ft^2), A_6 = area of 6-ft contour, A_o = area of subaerial land, D = depth of base, and V_p = volume of sediment in the delta prior to initiation of sedimentation. (Initial calculations were not made in metric units since all maps and charts were surveyed in feet.) The first term on the right side of Equation 1 is the volume from the base of the delta to 1.83 m (6 ft); the second term is from the 1.83-m contour to the 0-m subaerial-land contour. Estimates of volume determined from Equation 1 should be considered as a lower bound, since subsidence and sea level rise have effectively lowered the base of the receiving basin during deposition.

27. The rate of 0-m contour advancement was calculated by measuring linear progradation of subaerial land. For each survey, the subaerial extension of land was measured along a line normal to the apex of delta growth. Usually, the advance of sediments was normal to a primary channel that extended from a crevasse.

Sources of Error

28. The two main sources of error in a generic analysis of delta growth are (a) those inherent in the process of making the maps and charts, such as surveying, and (b) those resulting from subsequent laboratory analysis of the maps and charts, such as digitizing. Prior to the early 1920's, when techniques of aerial photography were first developed and applied (1930's in East Texas), maps and charts were constructed from land-based topographic and bathymetric surveys. Accuracy of these early surveys, conducted primarily by the U.S. Coast Survey (U.S. Coast and Geodetic Survey, now the National Ocean Survey), was dependent on scale and date of survey, standards in use for survey work, relative importance of the area surveyed, and the ability and care of individual surveyors (Shalowitz 1964). Such potential sources of error in the map-making process are well beyond the control of this study and cannot be quantified.

29. Despite the above limitations, early maps and charts appear to be surprisingly accurate. Perhaps the single most important variable in accuracy of a particular survey is its date; recent surveys are more

accurate than older surveys. The quality of maps took a quantum jump upward with the advent of aerial photography in the 1920's to 1930's. Errors in aerial photographs are related to resolution and distortion. Large-scale photographs have greater resolution, and the land-water boundary can be mapped with greater precision. Distortion of margins from optical aberrations can be largely overcome if only the central parts of the photograph are used or if photomosaics are constructed.

30. The land-water boundary can be difficult to delineate in deltaic marshland and can best be interpreted by those who have made observations in the field. With respect to this type of error, we have no choice but to trust the early engineers and take comfort in the assessment by Shalowitz (1964, p. 79):

> These (coast) surveys were executed by competent and careful engineers and were practically all based on a geodetic network which minimized the possibility of large errors being introduced. They therefore represent the best evidence available of the condition of our coastline a hundred or more years ago, and the courts have repeatedly recognized their competency in this respect.

31. Three types of errors are possible in the analysis phase: tracing, differential map distortion (expansion and contraction), and digitizing errors. Because many of the very old maps and charts did not circulate, it was necessary to make detailed tracings to be digitized at a later time. Comparison of traced areas to the available originals indicated that the difference in area was less than 1 percent, a value considered to be negligible. Distortion of old maps from stretching or shrinking as a result of humidity was also negligible. Each map or chart was individually scaled before digitizing, thus alleviating all but the most serious differential distortions.

32. The process of digitizing introduced the largest source of error. Although images for each delta were analyzed by one operator, small errors could not be entirely eliminated. This was particularly true in the case of the myriad of small delta lobes in the Mississippi subdeltas. Hundreds of detached segments of marsh surface had to be individually digitized to give the total land area. By comparing the results of an image digitized several times, it was found that a skilled operator could achieve results with a precision of 5 percent or less.

33. From a practical standpoint, the generic analysis is considered to be a combination of broad, long-term historical monitoring, as in the case of the 10 deltas and subdeltas, and restricted, short-term monitoring, as in the case of the Atchafalaya deltas. The advantage of long-term monitoring, described above, is that trends and relative values are more important than absolute accuracy. The advantage in short-term monitoring, described below, is that high-frequency events can be captured and the details of delta growth can be more accurately depicted.

Application and Analysis of Remote-Sensing Imagery

34. Short-term monitoring of deltaic sedimentation in Atchafalaya Bay was carried out using LANDSAT imagery and aerial photography. The availability of LANDSAT data every 9-18 days, depending on the number of satellites in orbit and the quality of images, provided high-frequency monitoring capabilities for relatively large areas. Yearly aerial photographic surveys at scales of 1:20,000-1:50,000, beginning in 1974, provided detailed mosaics for descriptive purposes. However, the inability to place the land-water boundary in its proper position relative to that on the maps and charts (mean high water) was a cause for concern, particularly when aerial photographs were to be compared with maps. This generally precluded the use of aerial photographs in the quantitative analysis.

35. Although LANDSAT data had the potential for high-frequency coverage under ideal conditions, only three to nine usable images could be acquired each year. High cloud cover during the overpass and on-board sensor problems were the major deterrents to clear images. As a general rule, computer listings were acquired only for images with cloud cover of less than 50 percent. These images, identified by a scene ID number, were examined on microfiche to determine whether or not they were suitable for purchase. Much of the initial screening and subsequent purchase of images was performed by the New Orleans District (courtesy R. H. W. Cunningham).

36. Two sensors aboard the LANDSAT satellite, the Multispectral Scanner Subsystem (MSS) and the Return Beam Vidicon (RBV), produce synchronous images at different wavelengths, each suited for a particular application. For good land-water discrimination, the near-infrared wavelengths of MSS band 7 (0.8-1.1 μm) give the sharpest boundary. The RBV sensor also provides a good land-water delineation but is not directly comparable to MSS band 7 because of a difference in resolution. A limiting characteristic of LANDSAT is that only features larger than 56 x 79 m (instantaneous field of view or pixel size) are sensed by the satellite, thus making very fine resolution impossible. Fortunately, even the small delta lobes in Atchafalaya Bay are larger than the pixel size.

37. The techniques used for analysis of LANDSAT data were slight modifications of those developed by Rouse, Roberts, and Cunningham (1978). The first step was to photographically enlarge each image from a scale of 1:1,000,000 to a scale of 1:50,000. Subaerial land was then traced onto vellum and digitized after the exact scale was determined. As in the case of historical maps and charts, variations in scale from one image to another were not of concern since the scale of each image was determined independently.

38. Because the amount of exposed land in Atchafalaya Bay is highly dependent on water elevation (as affected by stage of tide, river stage, barometric pressure, and wind speed and direction), it was necessary to obtain accurate information on water levels. Failure to perform this intermediate step would have resulted in apparent rates of change in subaerial land that were far greater than actual rates of growth or deterioration.

39. Water elevation at the time of satellite overpass was determined from tide records at three gages in Atchafalaya Bay: Deer Island Bayou (northern bay); Amerada Hess (midbay); and Eugene Island (southern bay) (Figure 6). Then, in order to remove the effects of water elevation from actual variations in land area, a plot of water elevation versus land areas was constructed for each flood year (usually defined as April 1 through March 31) (Figure 7). Finally, the amount of subaerial land

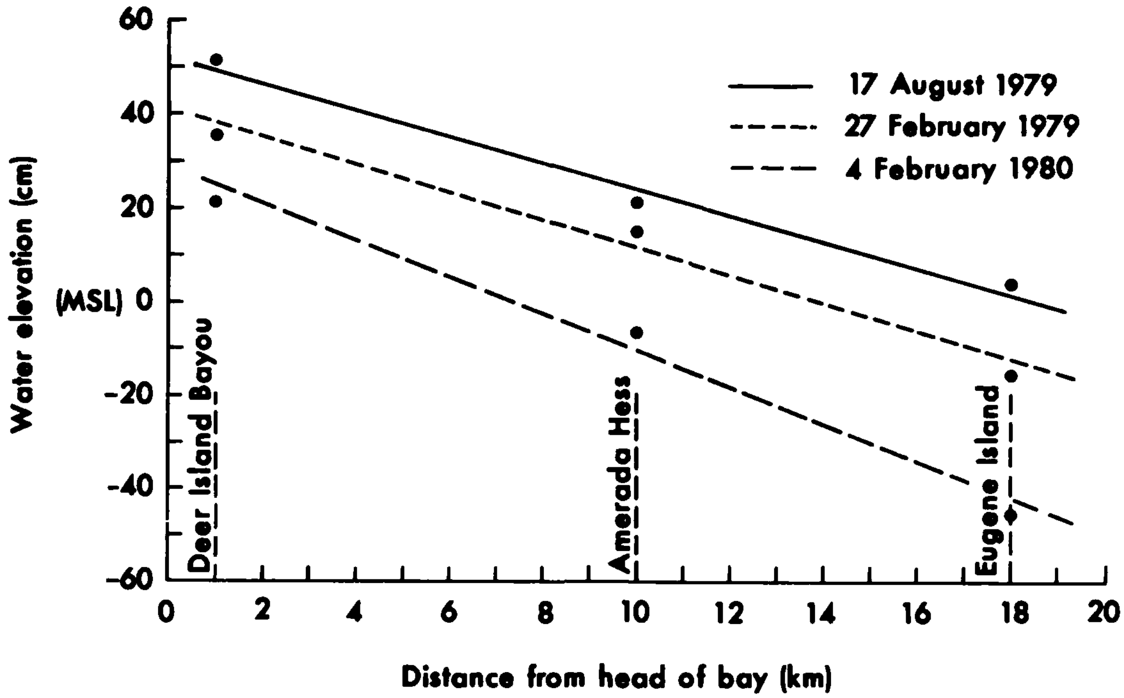

Figure 6. Examples of water elevation versus distance from head of Atchafalaya Bay. See Figure 1 for locations of three gaging stations. Water level at the time of satellite overpass was taken from the least-squares best-fit line at midbay position (Amerada Hess)

was determined from Figure 7 by constructing a nonlinear least squares fit to the data points for each flood year and extracting a value for subaerial land at the mean sea level position.

40. The above analyses were performed separately for the Wax Lake and Lower Atchafalaya River Deltas. Accordingly, a fourth tide gage record near the Wax Lake Delta, Point Chevreuil, was occasionally included in the water-level computations. The two sets of data, as determined from Figures 6 and 7, were then combined to provide yearly estimates of subaerial land for the entire Atchafalaya Bay. A listing of digitized LANDSAT images, corresponding water levels, and exposed areas in the Wax Lake and Lower Atchafalaya River Deltas is given in Appendix B.

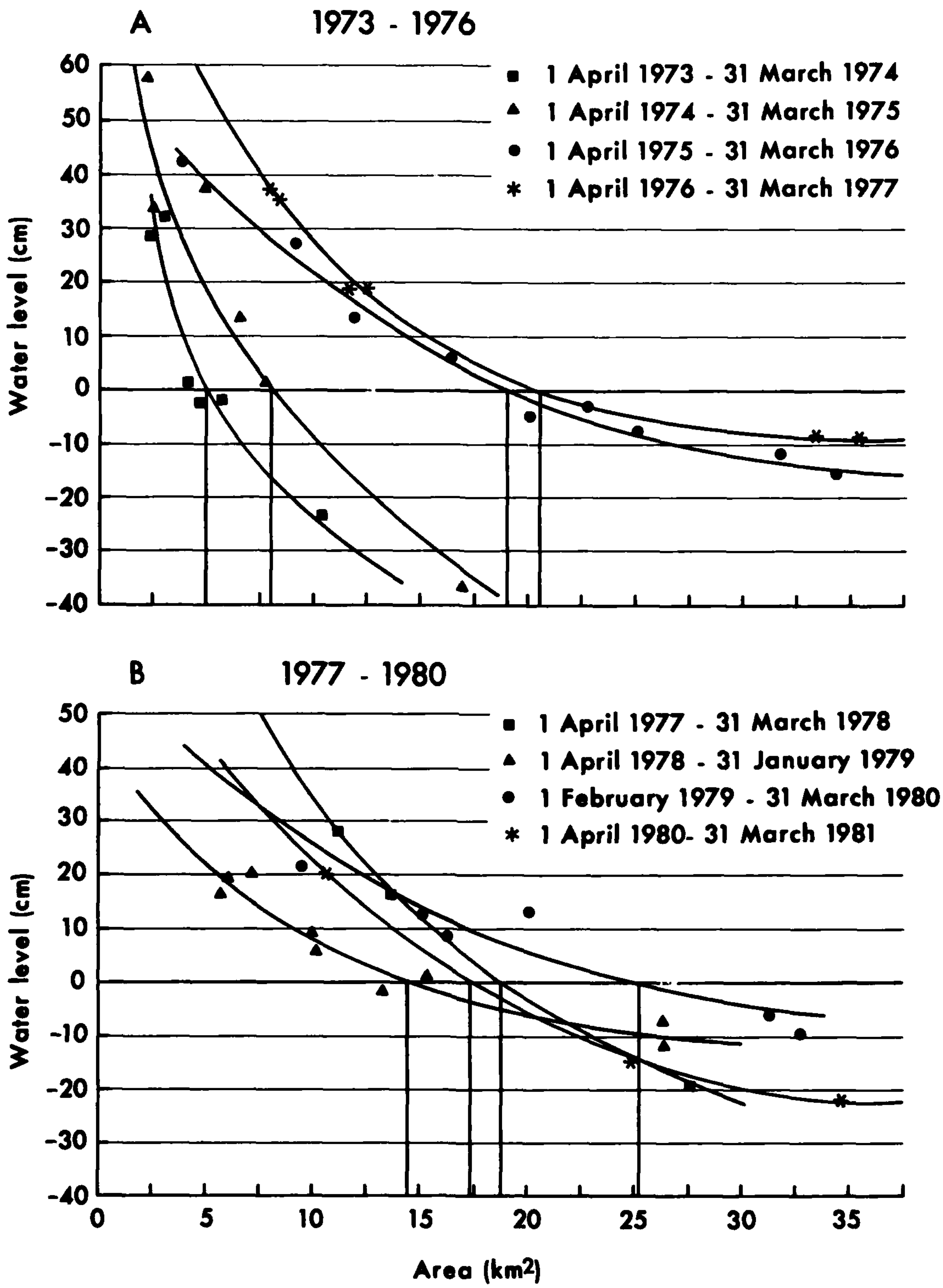

Figure 7. Water elevation versus area for each flood year, 1973-1974 through 1980-1981, in the Lower Atchafalaya River Delta (Wax Lake Delta not included). Subaerial land was determined from the nonlinear best-fit curves at mean sea level elevation (correlation coefficients range from 0.66 to 0.99)

PART III: RESULTS

East Texas Deltas

Guadalupe Delta

41. The Guadalupe Delta is the oldest and one of the smallest deltas used in the generic analysis. Initiated by sedimentation from discharge of the combined Guadalupe and San Antonio Rivers approximately 2000 years ago, it was constructed as a series of four subdeltas that reached a maximum area perhaps only slightly greater than its present area of 22.4 km^2 (Figure 8A). As in the case of the Atchafalaya Delta, the receiving basin is a shallow bay (<2 m) that is fringed by a barrier, Matagorda Island. Although the Guadalupe Delta is building into a low-wave-energy, low-current-strength environment, its rate of progradation is extremely slow because of a low, albeit highly variable, sediment discharge of only 8.8×10^5 metric tons/yr (Morton and Donaldson 1978).

42. The lack of a sufficient number of historic maps precludes the construction of a growth curve for Guadalupe Delta. However, sequential growth is shown diagrammatically in Figure 9. The process of growth has been by alternating subdelta lobes in a regressive sequence first to the southeast (Figure 9A, B), then to the northeast (Figure 9C, D). The bird-foot appearance was best developed during the Sommerville-Plank Bridge subdelta (Figure 9B), which formed as a result of the second major bifurcation on the lower Guadalupe River. Alternating bars from one side to the other along Guadalupe River suggest frequent abandonment of distributaries contemporaneously with delta growth (Donaldson, Martin, and Kanes 1970). The average rate of contour advancement has been approximately 12 m/yr. Assuming the initiation of the Guadalupe Delta to be 2000 years ago, the average rate of growth has been 0.01 km^2/yr, making it the slowest growing delta under consideration in this study.

43. The Guadalupe Delta is now largely in a state of deterioration. Examination of aerial photographs from 1929 and 1957 (Donaldson, Martin, and Kanes 1970) shows that the delta has transgressed over 60 m. Average rates of deterioration are reported to be 2.75 m/yr facing Guadalupe Bay

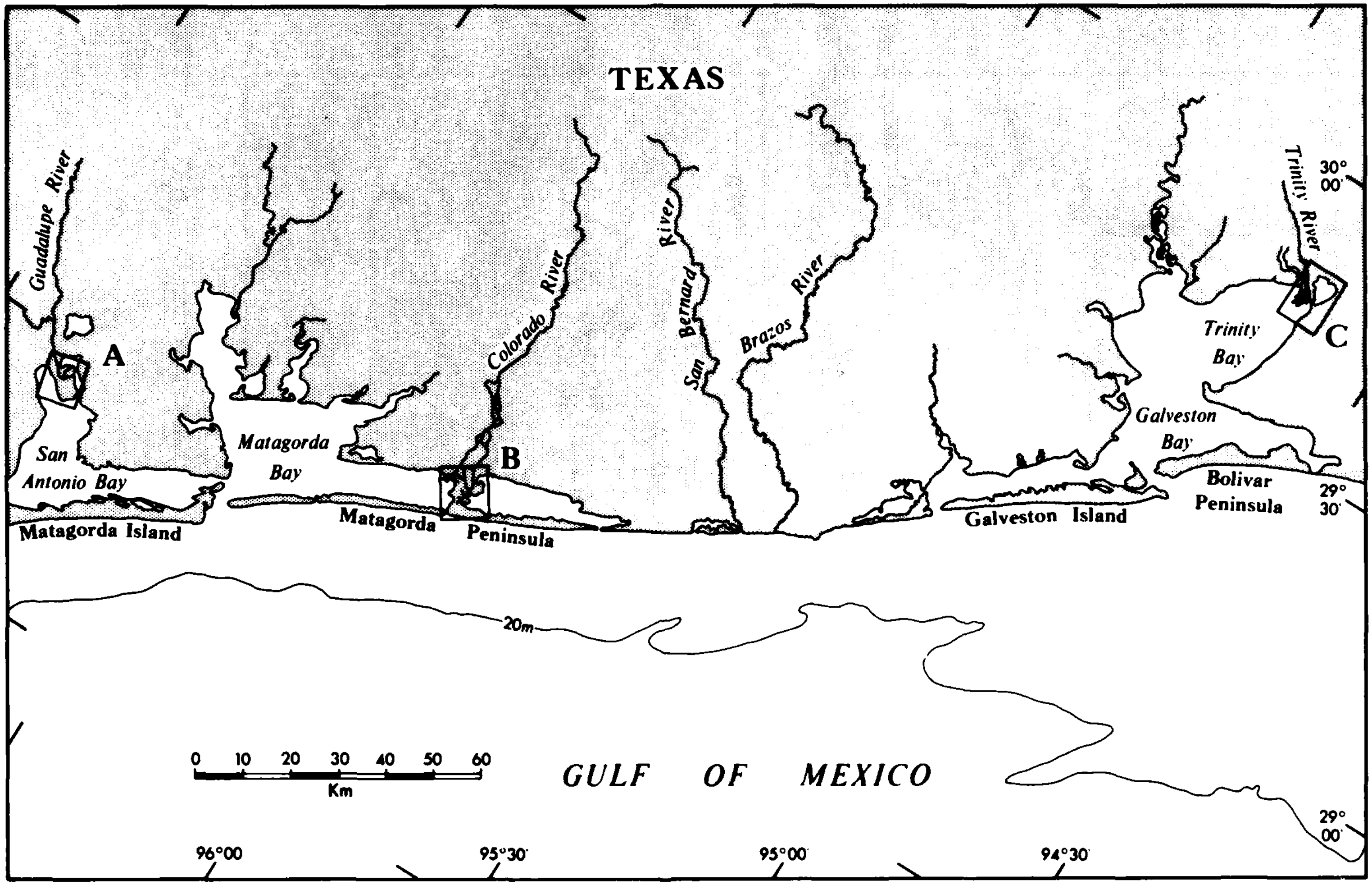

Figure 8. Index map of the Texas coast showing locations and configuration of the Guadalupe (A), Colorado (B), and Trinity (C) Deltas

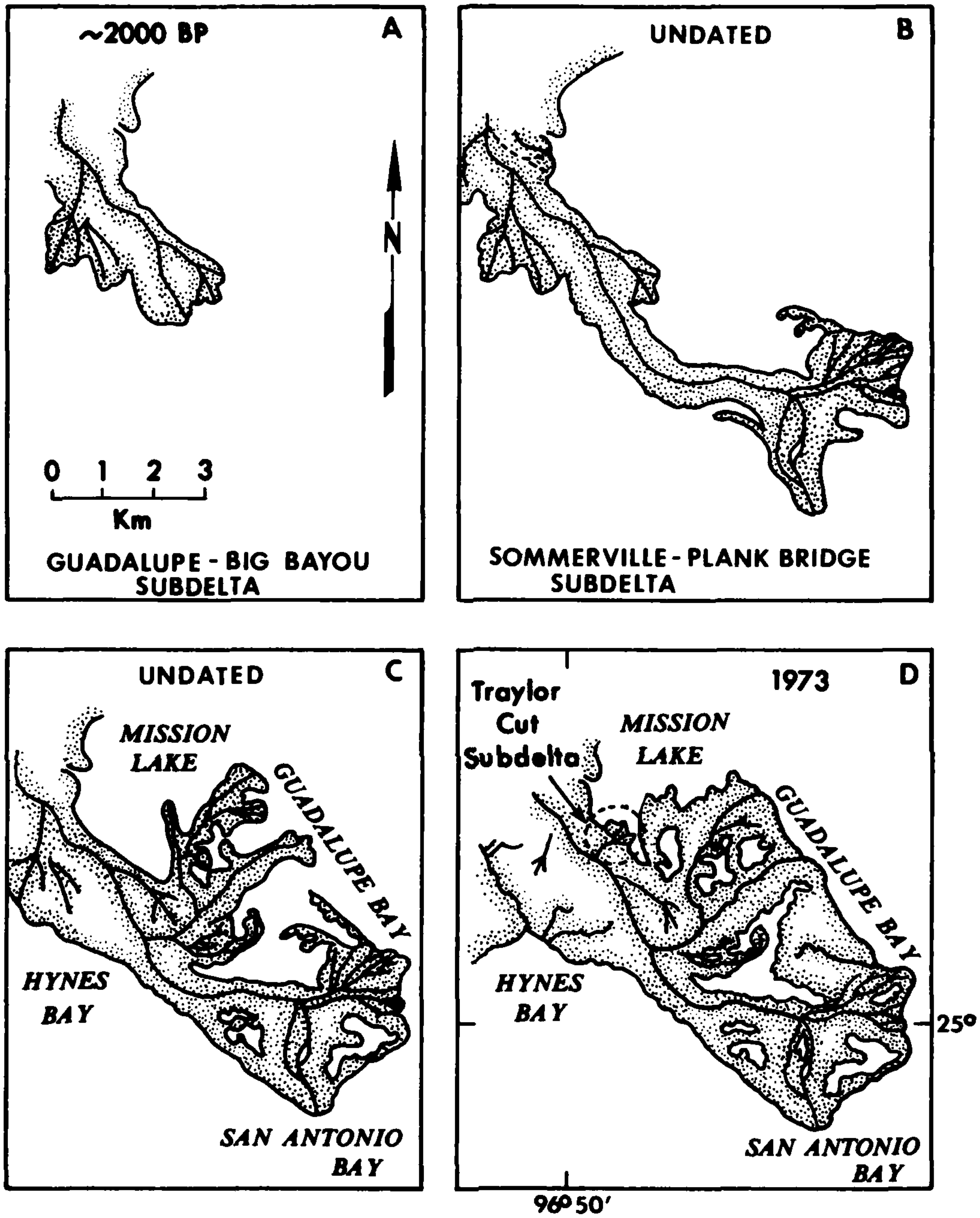

Figure 9. Holocene development of the Guadalupe Delta. A-C are from Donaldson, Martin, and Kanes (1970)

and 1.75 m/yr facing San Antonio Bay (Donaldson, Martin, and Kanes 1970). The only area of progradation, the Traylor Cut subdelta, began growing after an artificial cut between Guadalupe River and Mission Lake in 1935 (Figure 9). Increased flow through Guadalupe Bay from the Traylor Cut probably accelerated erosion along the southwest shoreline of the bay. As of 1973, the total area of Traylor Cut subdelta was 0.5 km^2, slightly greater than 2 percent of the total area of Guadalupe Delta. Sixty-five percent of the discharge flows through Traylor Cut, resulting in an average subdelta growth rate of 0.013 km^2/yr and a contour advancement rate of 23 m/yr.

Colorado Delta

44. During its rapid stage of development, the Colorado Delta prograded 8.1 km across the shallow (<2 m) Matagorda Bay in 6 years, making it the fastest growing delta in Texas. Progradation was initiated in 1929 after log jams that had blocked deltaic sedimentation since at least the 1600's (Wadsworth 1966) were cleared on the lower 46 km of the Colorado River. The process of deltaic infilling occurred behind a barrier, the Matagorda Peninsula, as a series of lobate and digitate subdeltas (Figure 8B). A partial barrier, the Dog Island Reef, helped restrict movement of the 11.6 x 10^6 metric tons/yr of incoming sediment to an area one-tenth the size of Atchafalaya Bay.

45. Evolution of the Colorado Delta can be divided into four phases, each tied to a well-defined sequence of events controlled largely by man. The first phase was slow sedimentation before and during removal of logs between 1925 and 1929. The 1908 survey, the first detailed map of the delta, showed only 0.19 km^2 of deltaic sediment deposited as a small bulge west of the Colorado River outlet (Figure 10A). Between 1908 and 1929, average growth rates of 0.24 km^2/yr (Figure 11) were probably a result of fine-grained sediments carried over and around the log rafts during major floods. The final removal of the log barrier, aided by the flood of 1929, constituted an event equal in magnitude to the opening of a major crevasse on the lower Mississippi River.

46. The second phase of development was characterized by uniform and rapid growth. Between 1929 and 1941, four lobes formed and coalesced to build a total of 23.5 km^2 of new subaerial land at an average rate of 1.9 km^2/yr (Figure 11). The first lobe formed 7.2 km^2 of subaerial

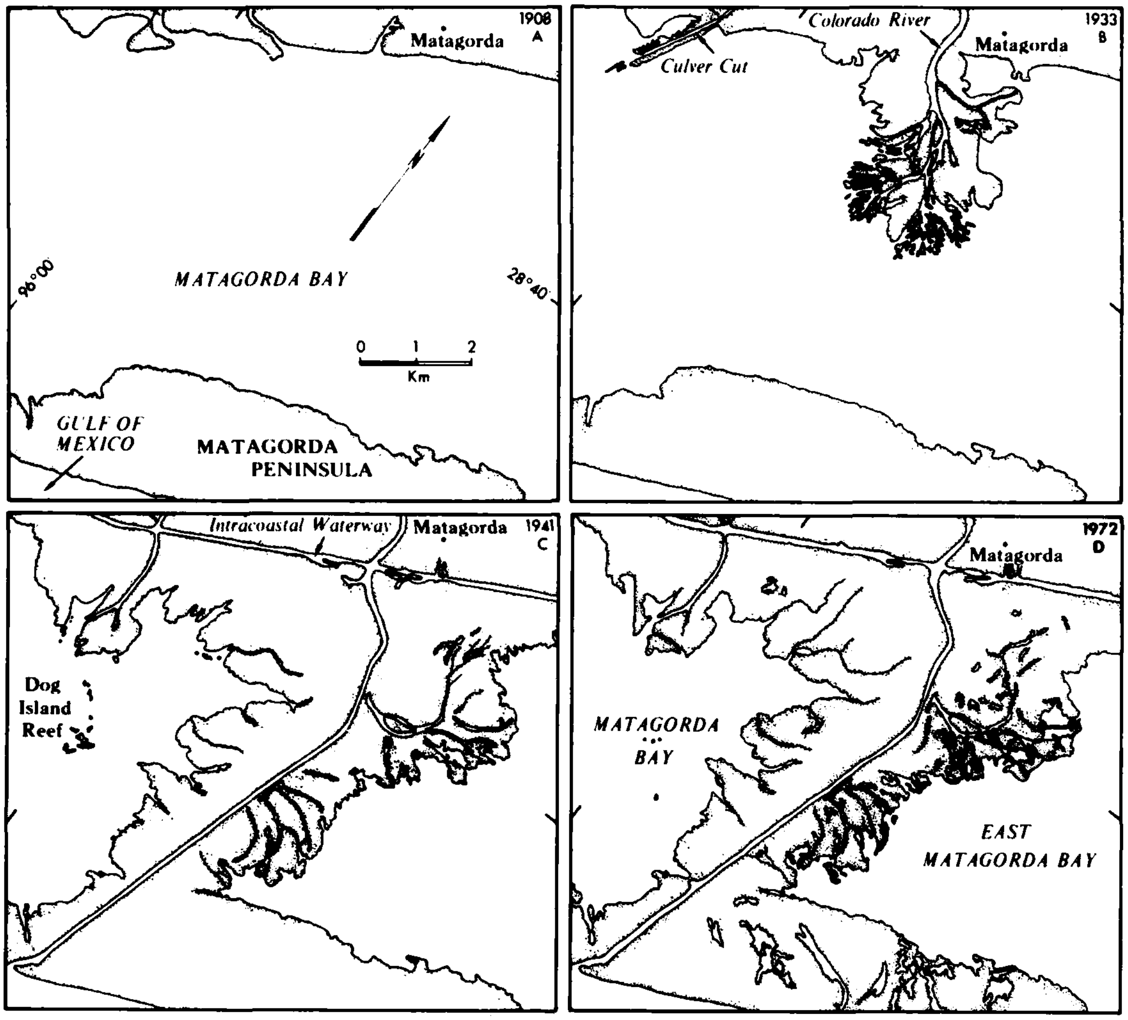

Figure 10. Development of the Colorado River Delta between 1908 and 1972

land in 1930 that extended halfway across the bay. This lobe was constructed from the normal sediment load of the Colorado River, together with resuspended coarse sediments that had been deposited above the log raft (Manka and Steinmetz 1971). By 1933, a more digitate northeast lobe had encircled the earlier lobe (Figure 10B). Distributaries had become better developed and were spaced farther apart. After a major flood in the spring of 1935, a dredged channel was extended across Matagorda Bay, then through Matagorda Peninsula in 1936. Simultaneously with

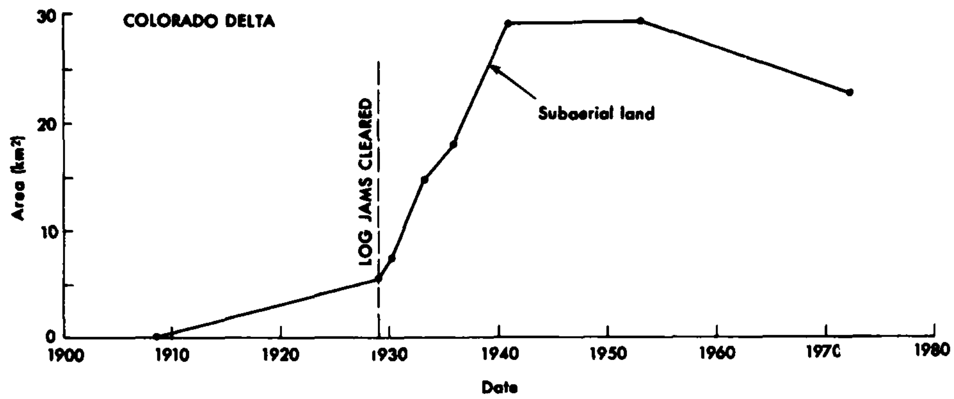

Figure 11. Subaerial growth of the Colorado River Delta (taken primarily from Wadsworth 1966)

dredging, the northeast lobes (combined 1930 and 1933 lobes) ceased to develop and a new southeast lobe prograded across the bay, thus forming a land bridge to Matagorda Peninsula by late 1935. The fourth and final lobe was an enlargement between 1935 and 1941 of the three earlier lobes (Figure 10C). Artificial levees and a farm road virtually sealed off sediments to the bay after 1941.

47. A period of stabilization occurred between 1941 and 1952. Minor new growth, mainly from reworked sediments deposited prior to 1941, added an average of 0.03 km^2 of subaerial land per year (Figure 11). The peak of subaerial development at 29.1 km^2 in 1952 marked the end of the stable period, and the Colorado Delta entered a slow destructional phase. Interdistributary bays began forming, the shoreline became more crenulated, and small beach ridges were deposited by storm waves (Figure 10D). Between 1952 and the latest survey of 1972, an average of 0.34 km^2/yr of subaerial land was lost. Moreover, during the 46 years since the Gulf of Mexico became the receiving basin for sediments of the Colorado River (1935), subaerial land has not formed seaward of Matagorda Bay.

48. Volume estimates of sediment fill after 1929 were based on data from two sources. The first was an isopach map provided by Kanes (1970); the second was computed from the USGS Matagorda Quadrangle, photo-revised to 1972. Without a 1952 bathymetric chart, it was not

possible from these data to determine whether or not sediments were deposited subaqueously after subaerial growth ceased in 1952. However, assuming that volume has increased continuously, calculations indicate an average rate of fill of $3.6 \times 10^6\ m^3/yr$. Rate of contour advancement indicated that only two pulses of forward growth were present during progradation of the Colorado Delta. The first, corresponding to development of the northeast lobes, occurred between 1908 and 1930; the second corresponded to development of the southeast lobe btween 1933 and 1935. Advance of the delta after 1935 was prevented by the Matagorda Peninsula.

Trinity Delta

49. The Trinity Delta is a small bayhead delta that has developed in the northeast segment of the shallow (2-3 m) Trinity Bay (Figure 8C). Separated from the Gulf of Mexico by discontinuous oyster reefs in central Galveston Bay and by Galveston Island and Bolivar Peninsula in southeastern Galveston Bay (Figure 8C), the Trinity Delta is located 48 km from open-water conditions. Progradation of the delta began after the mouth of the Trinity River shifted to the east side of Trinity Valley approximately 500-800 years ago (McEwen 1963). Although the Trinity River has the highest discharge of any river in Texas, its sediment load is only 5.0×10^6 metric tons/yr, a value considerably less than that of the Brazos, Rio Grande, or Colorado River. Thus the small size of the delta, 13.5 km^2 as of 1974, is explained partly by the limited sediment input.

50. Growth of the Trinity Delta has been traced pictorially from surveys of 1855, 1933, 1942, and 1961 (Figure 12). The delta grew outward from the eastern margin of the Trinity alluvial valley, isolating a small segment of Trinity Bay referred to as Lake Anahuac (Figure 12A, B). Between 1855 and 1933, subaerial land grew in size from 7.8 to 10.8 km^2 at an average rate of 0.04 km^2/yr (Figure 13). To ease the flooding problems in the city of Anahuac, a channel was dredged parallel to the shoreline, directing the Trinity River away from the city (Figure 12C). Average growth rate increased to 0.11 km^2/yr between 1933 and 1961; the peak of delta development was 13.9 km^2 in 1961. A 1974 photo revision of the 1961 Anahuac Quadrangle showed slight deterioration

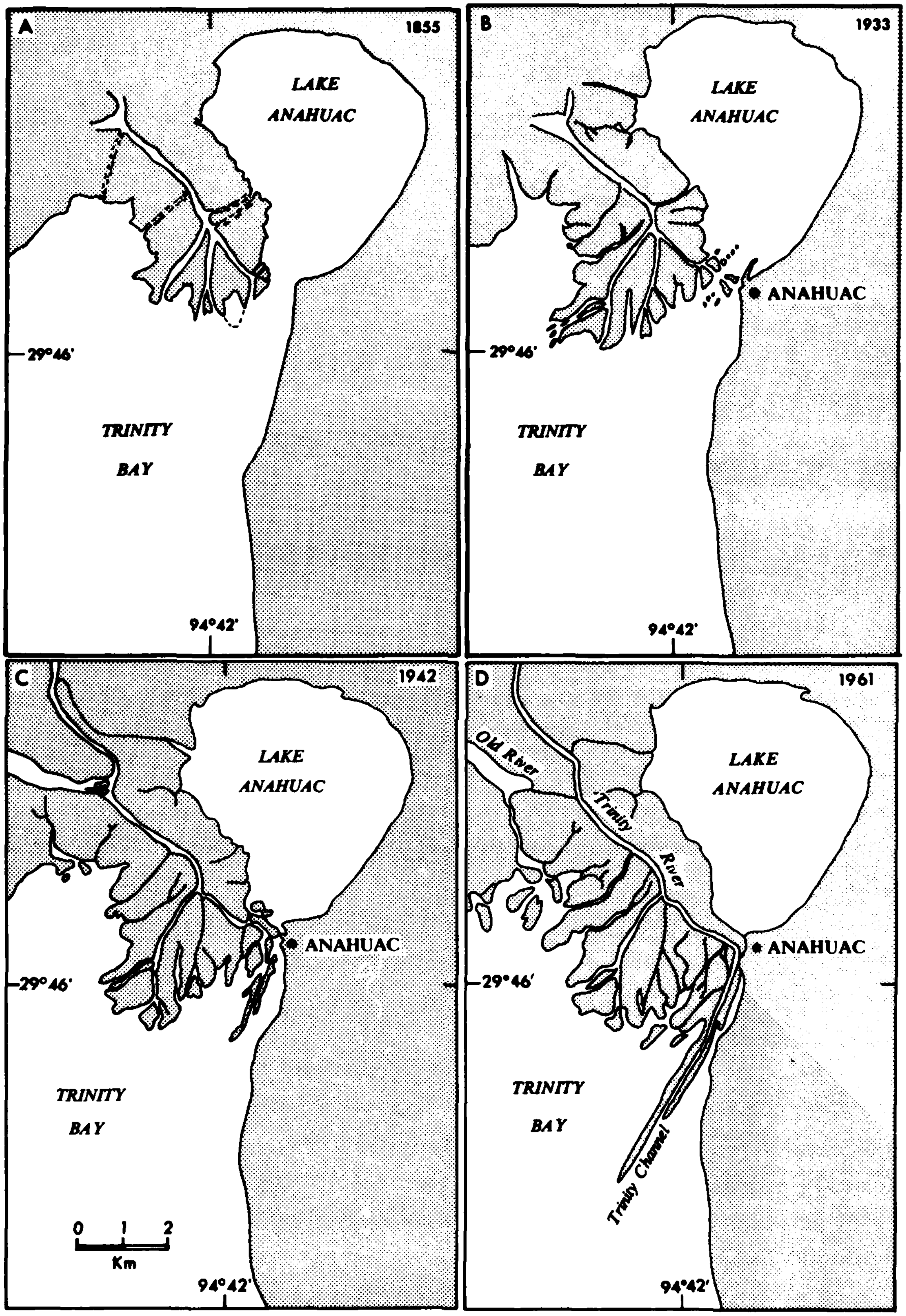

Figure 12. Development of the Trinity River Delta between 1855 and 1974

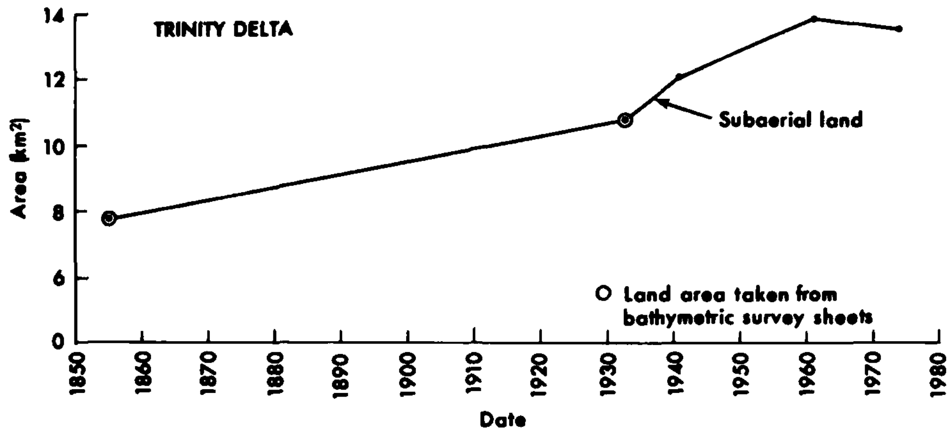

Figure 13. Subaerial growth of the Trinity River Delta (data from C&GS and USGS maps and charts)

of deltaic marsh and several distributaries that had been abandoned since 1855 (Figure 12D).

51. Although curves for volume and contour advancement were not constructed because of the limited number of available maps, the rates for these variables since the mid-1800's can be summarized as follows: (a) the development of 5.7 km^2 of subaerial land in the past 119 years has caused most of the upper Trinity Bay to shoal by 0.5 m, with localized infilling near the delta on the order of 1-2 m; and (b) contour advancement during the same time period has been 0.5 km to the southeast at an average rate of 4 m/yr.

Foreign Deltas

Laitaure Delta

52. The Laitaure Delta, located in northern Sweden at an elevation of 495 m above sea level, has formed as a small lacustrine delta in Lake Laitaure from sediments of the Rapaälven River. It has a subaerial exposure of only 10 km^2 and is supplied by a sediment discharge of 1.9 x 10^5 metric tons/yr. Glaciers comprise 12 percent of the total drainage area, and the Laitaure Lake and Delta are frozen from surface to bottom during winter months. Sediment discharge is thus highly variable, with

95 percent of total annual discharge occurring during the months of June-August and one-half occurring within a 5-day period usually in July (Axelsson 1967). Although the Laitaure Delta bears little overall resemblance to the Atchafalaya Delta in terms of the process variables in Tables 1 and 2, it is quite similar in that (a) delta growth began after several lakes upstream became sediment-filled and (b) morphology of the filled areas resembles that of Grand and Six Mile Lakes in the Atchafalaya Basin and that of the eastern half of the Lower Atchafalaya River Delta.

53. The Laitaure Delta is an elongate rather than lobate delta that is restricted by the width of Lake Laitaure. It thus serves as an excellent example of deltaic growth in a very confined receiving basin some 15 km long, 1-2 km wide, and 4 m deep (Figure 14). Because the lake and drainage basin are highly inaccessible and of no economic importance with respect to shipping, they are rather poorly known geographically and geologically. No survey data exist for comparison purposes, and the data presented here are taken from the published work of Axelsson (1967).

54. Figure 15 shows the delta front from tracings of aerial photographs taken in 1954, 1960, and 1963. Although this sequence shows subaerial land at three different water levels, it nevertheless indicates the speed with which delta-front changes can occur. For example, the 1963 configuration at the high-water level of 1.29 m shows that at least one small channel had been sealed and that growth had occurred since 1954 via extension of channels and parabolic delta lobes. As of the mid-1900's, one-half of Lake Laitaure was filled with deltaic sediments.

55. The most characteristic features of the Laitaure Delta are the active and abandoned channels, levee ridges, and interlevee basins. Channels are branching, with average water depths of 1-2 m. At low water stage, channels appear to be braided. Smaller channels may be closed at their heads, causing the flow network to vary considerably from high to low water. Historically, as the Laitaure Delta prograded and filled in the upper reaches of the lake, older channels were abandoned. These now show signs of deterioration. New channels that were excised

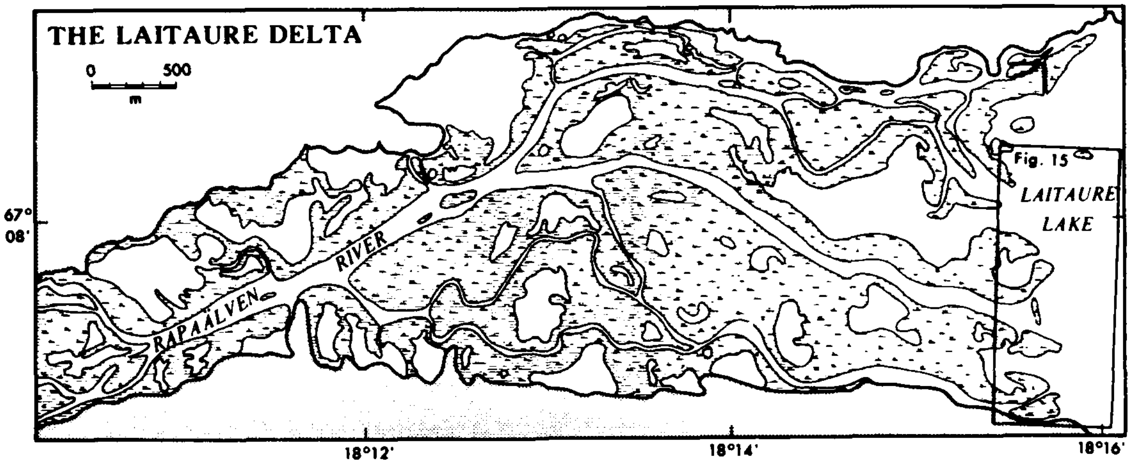

Figure 14. The Lake Laitaure Delta, in northern Sweden

into marginal lakes produced miniature deltas. Unlike any other delta in the generic analysis, the pattern of sedimentation was influenced by two important factors. First, the irregular topography of the receiving

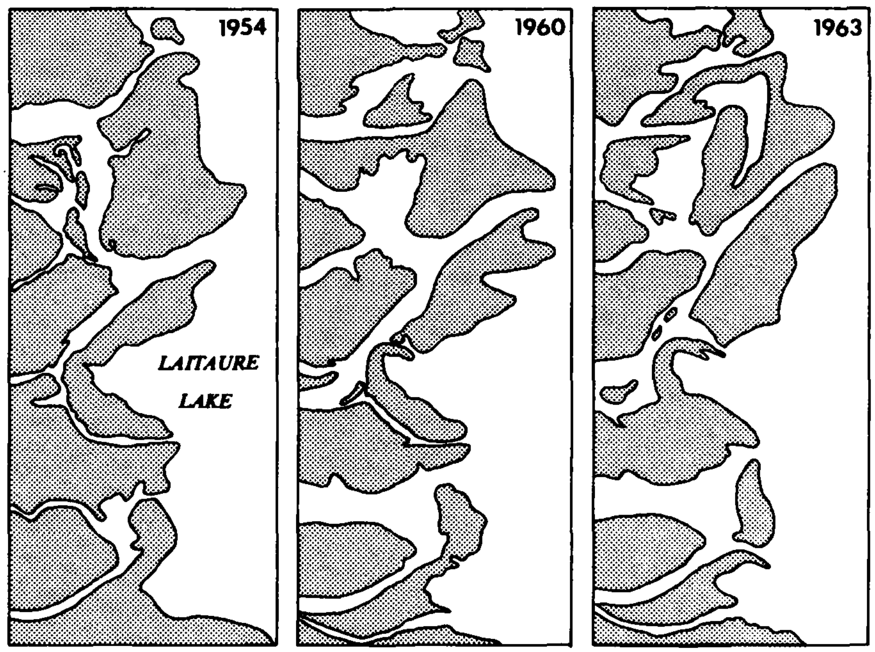

Figure 15. The Lake Laitaure delta front in 1954, 1960, and 1963 at lake stages of 1.00, 1.23, and 1.29 m, respectively (taken from aerial photographs, Axelsson 1967)

basin partly controlled locations of channels and subaerial land. Second, the single annual pulsation of sediment to the delta over a short interval of time produced one-half of the delta growth in a single week of catastrophic deposition each year, with no subsequent opportunity for reworking by longshore currents, tidal currents, or waves. Projected rates of infilling by Axelsson (1967) indicate that Lake Laitaure will continue to fill in this fashion for another 1000 years.

Catatumbo Delta

56. The Catatumbo Delta, on the southwest shore of Lake Maracaibo, Venezuela, is a small lacustrine delta that serves as a modern analogue to the intermontane deltas that were common in the Tertiary (Figure 16). The delta has formed from sediments delivered by the Catatumbo River at a rate of approximately 9×10^6 m^3/yr (Hyne, Cooper, and Dickey 1979). Free connection with the Caribbean Sea through the Strait of Maracaibo allows waters to become slightly brackish, depending on rainfall, and for the introduction of tides on the order of 6-22 cm (Redfield 1961).

57. During historic times, five to seven delta lobes were deposited over a total area of roughly 750 km^2. Each lobe appears to have remained active for 100 years, after which time delta switching resulted in a new site of deposition. Abandoned deltas are rapidly eroded by waves generated from the northeast trade wind system. A map of shoreline changes shows that between 1928 and 1975 transgression and regression have occurred simultaneously within the Catatumbo Delta and vicinity.

58. Presently there are two distributaries on the modern Catatumbo Delta, one discharging to the northeast, the other to the southeast. Results of map studies undertaken by Hyne, Cooper, and Dickey (1979) indicate that the north and south distributaries have prograded since 1917 at average rates of 76 m/yr and 22 m/yr, respectively. Accurate surveys from 1928, 1930, and 1949 were digitized to determine subaerial land growth rate. Subaerial land grew at a rate of 0.01 km^2/yr during this 21-year period. Additional data cited by Hyne, Cooper, and Dickey (1979) indicate that approximately 130 km^2 of lacustrine depositional plain are covered by prodelta sediments.

59. Maps show that both distributaries of the Catatumbo Delta

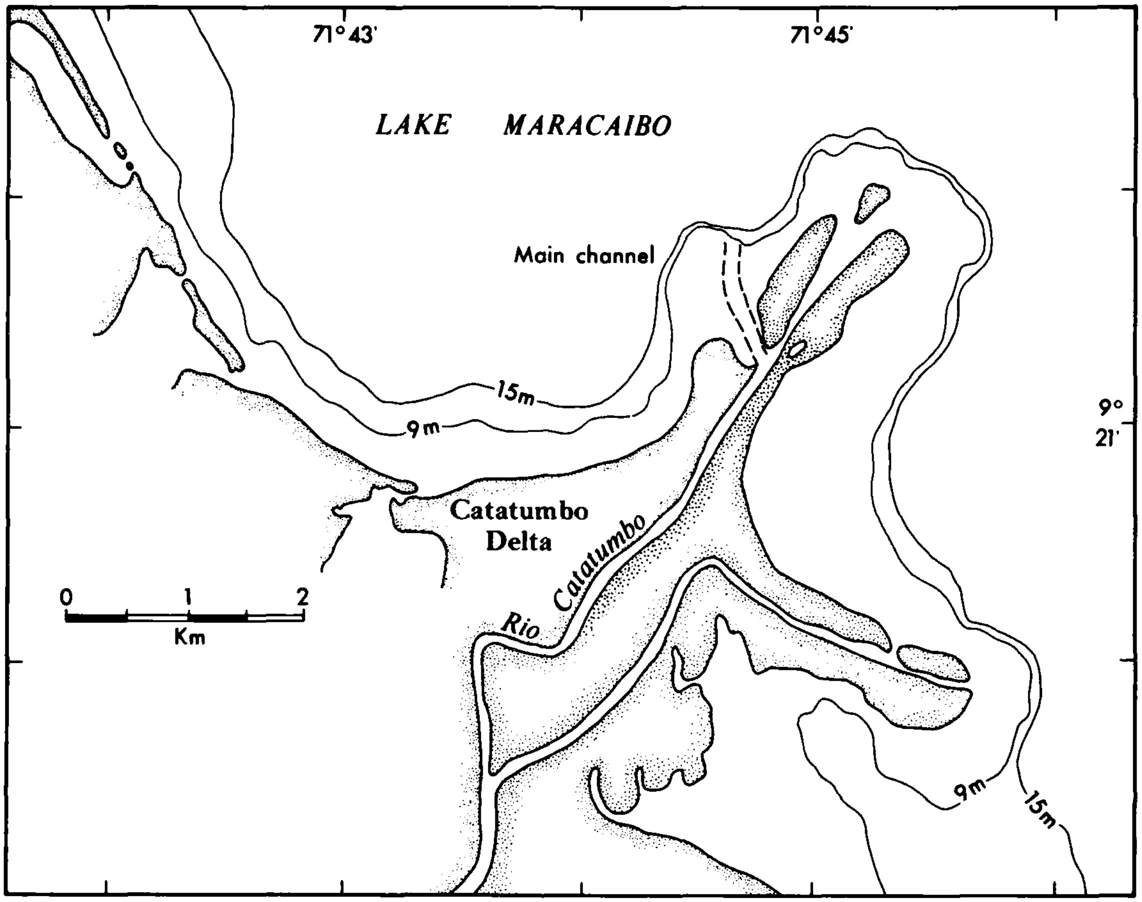

Figure 16. The Catatumbo Delta, in Lake Maracaibo, Venezuela

have a well-developed triangular middle-ground bar and that both lack abundant crevasse systems and subdelta lobes similar to those that are so common on the Mississippi Balize Delta. Channels are considered to be exceedingly stable; Hyne, Cooper, and Dickey (1979) attribute this to dense jungle vegetation and the relative lack of tides to impound river water, thus forcing it through crevasses. Unlike the other deltas in the generic analysis, the Catatumbo Delta appears to build by channel extension without bifurcation. The channels to either side of the bar are not symmetrical, and the deeper channel periodically shifts from one side to the other. Bed load sediments are spread in a width 16 times greater than the width of the orifice.

Danube Delta

60. The Danube Delta, in eastern Romania, the largest of the deltas and subdeltas used in the generic analysis, protrudes 35 km into the western margin of the Black Sea (Figure 17A). The 5000 km^2 Holocene subaerial delta is divided into three segments by three major distributaries, the Chilia, Sulina, and Gheorghe. Eighty-seven percent of the subaerial delta is marshland or "river flats," derived from an annual sediment discharge of 61.3×10^6 metric tons/yr.

61. The first of five recognized delta lobes was initiated by sedimentation approximately 6000 years ago (Panin 1976). Prior to this early lobe, a long spit that followed the curvature of the Romanian shoreline had formed from longshore drift to the south. During the next 4000 years, four subdeltas prograded beyond the Letea-Caraoman spit, each with a life cycle of 1000-3000 years (Panin 1976). Although two of these subdeltas are active today, only one, the Chilia, is presently prograding (Figure 17B).

62. The Chilia subdelta takes 63 percent of total river discharge and perhaps an equal percentage of the sediments. According to Panin (1976), it began prograding nearly 2000 years ago when the Chilia distributary breached the Letea-Caraoman spit and entered the marine environment. Since 1830 the Chilia subdelta has more than quadrupled in areal extent and increased threefold in volume (Figure 17C). The rates of growth have been rather uniform since the 1830 survey; subaerial land and total volume have increased at average rates of 2.3 km^2/yr and 0.05 km^3/yr, respectively. A relatively large volume to area ratio, 7.2 km^3 for 330 km^2 of subaerial land, indicates that the Chilia subdelta is now building into a deep receiving basin. Present rate of extension of the Chilia subdelta is 50-80 m/yr (Kravtsova, Ushakova, and Chekalina 1979).

63. Variations in total subaerial land in the Danube Delta between 1888 and 1972 have been obtained from a data set presented by Kravtsova, Ushakova, and Chekalina (1979) and are summarized below. The complex river network of the three main distributaries and their primary branches has been remarkably stable. This has been partly a result of engineering works between 1868 and 1902 that shortened the central Sulina distributary

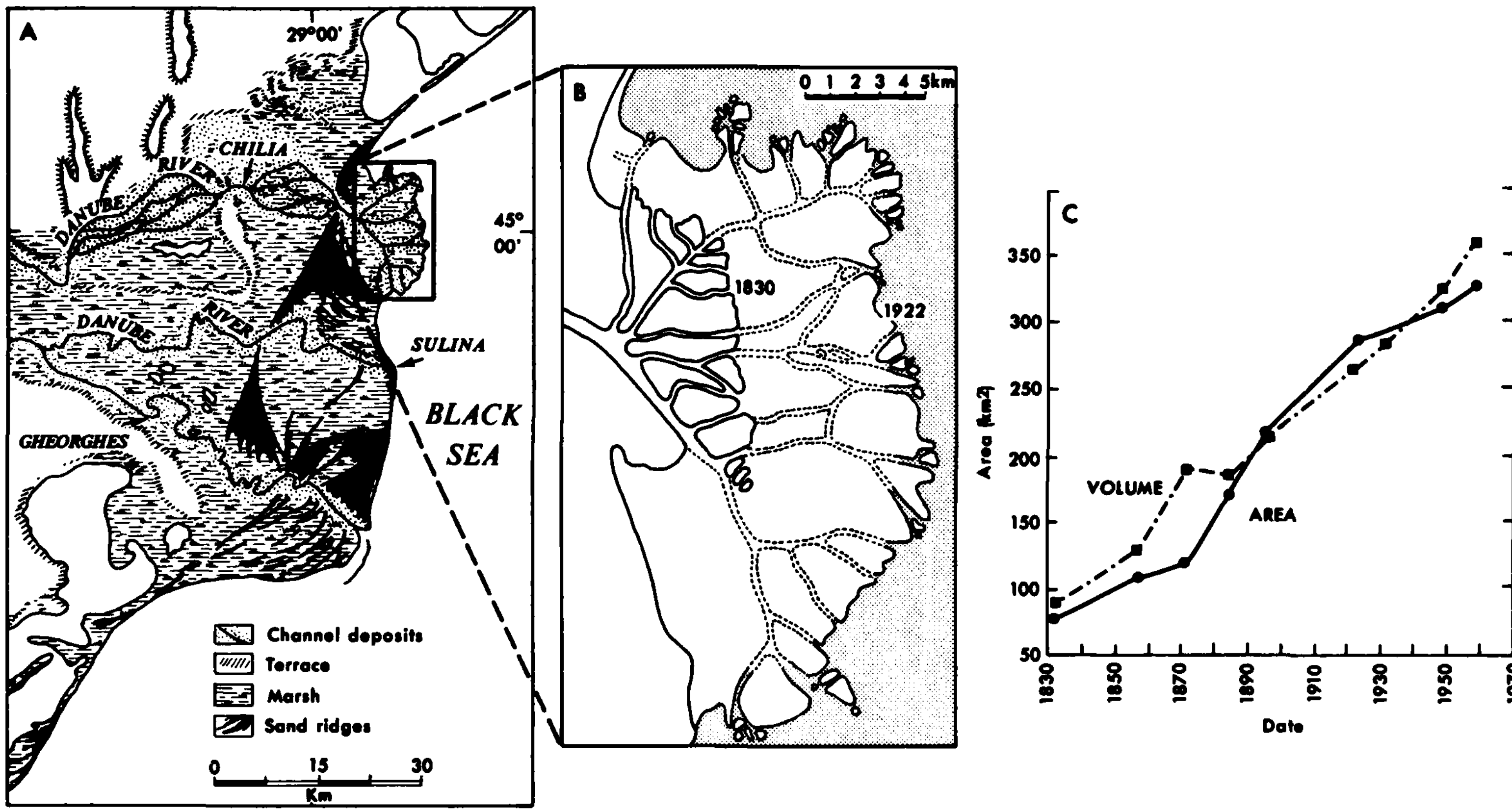

Figure 17. Index map of the Danube Delta in eastern Romania showing configuration and rate of growth. A. Distributaries and major segments of the Danube Delta. B. Progradation of the Chilia subdelta between 1830 and 1922. Dashed lines represent extensions of distributaries (from Petrescu 1968). C. Area and volume growth curves for the active Chilia subdelta (from Almazov et al. 1963)

by 25 percent to prevent flooding and to stabilize flow. During the last 84 years, approximately 26 km^2 of small distributaries have ceased to function and 7 km^2 of new streams have formed. Whereas 103 km^2 of lakes have filled with sediment and grown over with marsh vegetation, 241 km^2 of new lakes have developed from subsidence and 578 km^2 of "estuary" lakes have appeared in the southeastern part of the delta at the sites of bays cut off by longshore drift. Further, nearly 150 km^2 of beach ridges that marked positions of former shorelines in the southeastern Danube Delta have been submerged by the effects of subsidence. The only figures available for retreat of the delta shoreline indicate average rates of 10 to 15 m/yr south of the Gheorghes distributary.

Mississippi River Subdeltas

64. Four Mississippi River subdeltas have been active since the first accurate survey of the Mississippi River delta in 1838 by Captain A. Talcott. Three of the subdeltas lie above Head of Passes (Figure 18) and together take, via flow through crevasse systems, approximately 18.4 percent of flow that reaches the lower Mississippi Delta (Morgan 1977). Although similar in many respects, the subdeltas vary in size, geometry, depth of receiving basin, and exposure to wave attack.

Baptiste Collette

65. The smallest Mississippi River subdelta, the Baptiste Collette, began its growth in 1874 after a crevasse broke through the small Baptiste Collette Bayou canal. Sediments were carried northeast into the sheltered Bird Island Sound (Oyster Bay) and deposited in water less than 2 m deep. The pattern of growth was relatively uniform and lasted 72 years (1874-1946); the growth period was followed by a period of stabilization (1946-1958), then rapid deterioration beginning in 1958 (Figure 19). Discharge data from Corps of Engineers (CE) records indicate that flow through the crevasse increased from 2.6 percent of the total during the early years of growth (average discharge for 1915-1922) to 3.9 percent during the years of stabilization and deterioration (average discharge for 1949-1974).

66. The first chart to show a subaerial delta, published in 1893

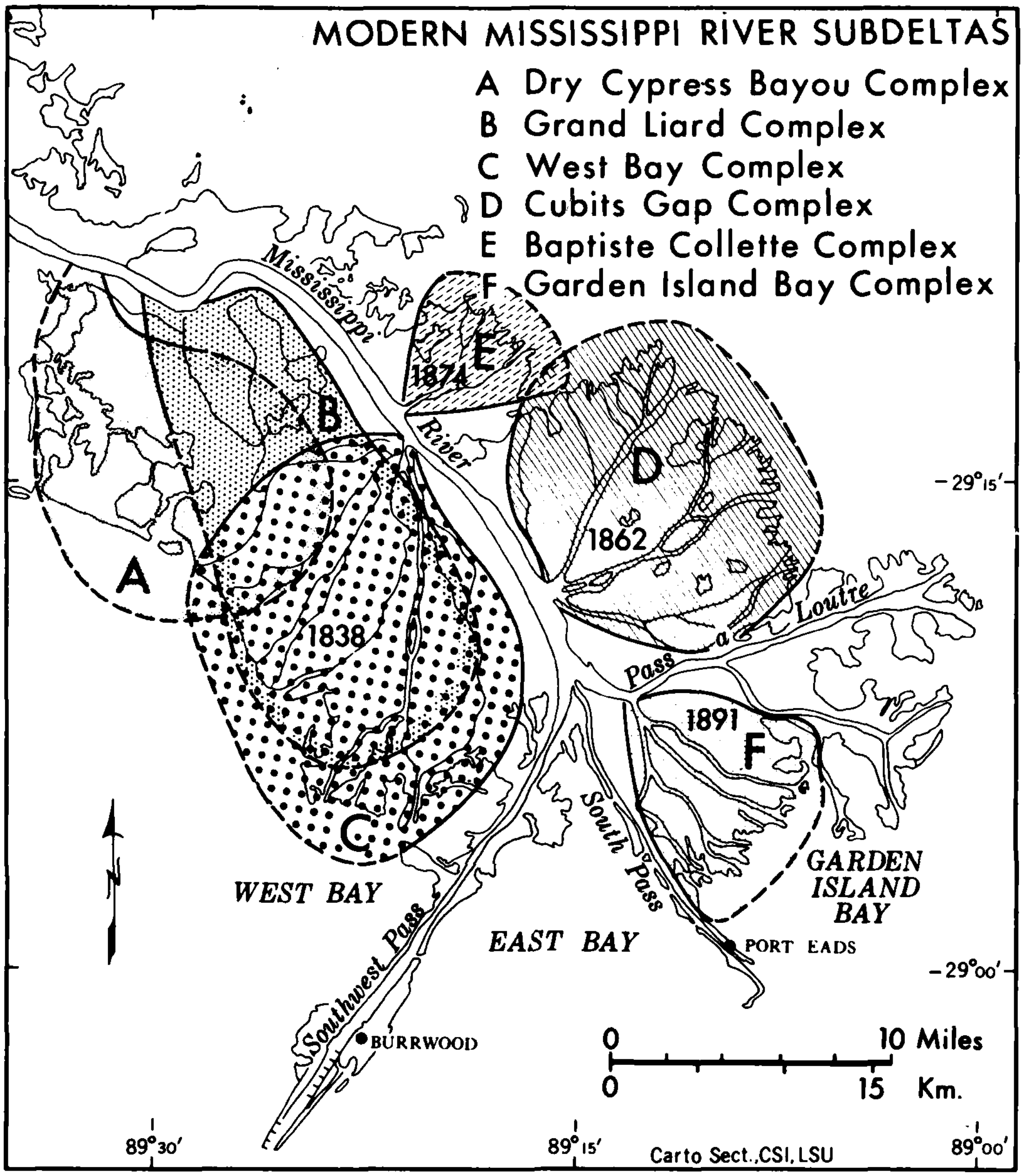

Figure 18. Six subdeltas of the modern Mississippi Balize Delta recognized from maps and sediment analysis. Dates indicate year of crevasse opening (Dry Cypress Bayou and Grand Liard subdeltas not included in this study)

(1891 survey), indicated that initial growth was slow and amounted to only 2.4 km^2 in 17 years (Figure 19A). The most rapid subaerial growth occurred during the next 17 years (1891-1908) as sands gained subaerial exposure by prograding over the prodelta/distal bar base of fine-grained sediments. In 1908, the CE dammed the Bayou Baptiste Collette crevasse, thus temporarily halting subdelta growth for 7 years (Figure 19A). The dam was breached by high water in 1915 (Morgan 1977), and a new phase of growth began that lasted until 1922. Between 1922 and 1932, the Baptiste Collette subdelta merged with the Cubits Gap subdelta, causing accelerated growth at their junction but slower growth within the defined boundaries of the Baptiste Collette system. Although the subdelta reached its maximum subaerial extent of 57.2 km^2 in 1946, rapid deterioration did not begin until 1958. Maximum rate of deterioration (1.8 km^2/yr) exceeded maximum rate of growth (1.1 km^2/yr). An increase in subaerial land of 4.4 km^2 occurred during the destructional phase as a result of abnormally high flood years between the 1971 and 1978 data points (Figure 19A).

67. Figure 20 shows, from selected surveys, the representative patterns of growth and deterioration. Major bifurcations on Baptiste Collette Bayou (the main channel) occurred prior to 1922. During stabilization, after 1946, the smaller inefficient channels sealed and sedimentation was just capable of offsetting subsidence. Figure 19B shows that during this period of subaerial stabilization both sediment volume and linear growth continued to increase. Further, the most rapid increase in volume (0.013 km^3/yr) occurred not only during stabilization but throughout the destructional phase as well (Figure 19B). By 1959 land extended 12.9 km into Oyster Bay, and by 1971 0.75 km^3 of sediment had been deposited in the Baptiste Collette subdelta.

Cubits Gap

68. The Cubits Gap subdelta has been one of the most thoroughly studied subdeltas of the Mississippi River, primarily as a result of the work by Welder (1959). Since the opening of the crevasse in 1862, sediments have been filling the relatively deep (9 m) Rondo Bay receiving basin to the northeast. A trifurcation established in the 1870's at the crevasse opening allowed flow to follow three major passes, referred to (from north to south in Figure 18) as Main Pass, Octave Pass, and Raphael Pass. The Cubits Gap subdelta is approximately four times as large as Baptiste Collette and takes 12.5-14.5 percent of total river discharge above Head of Passes.

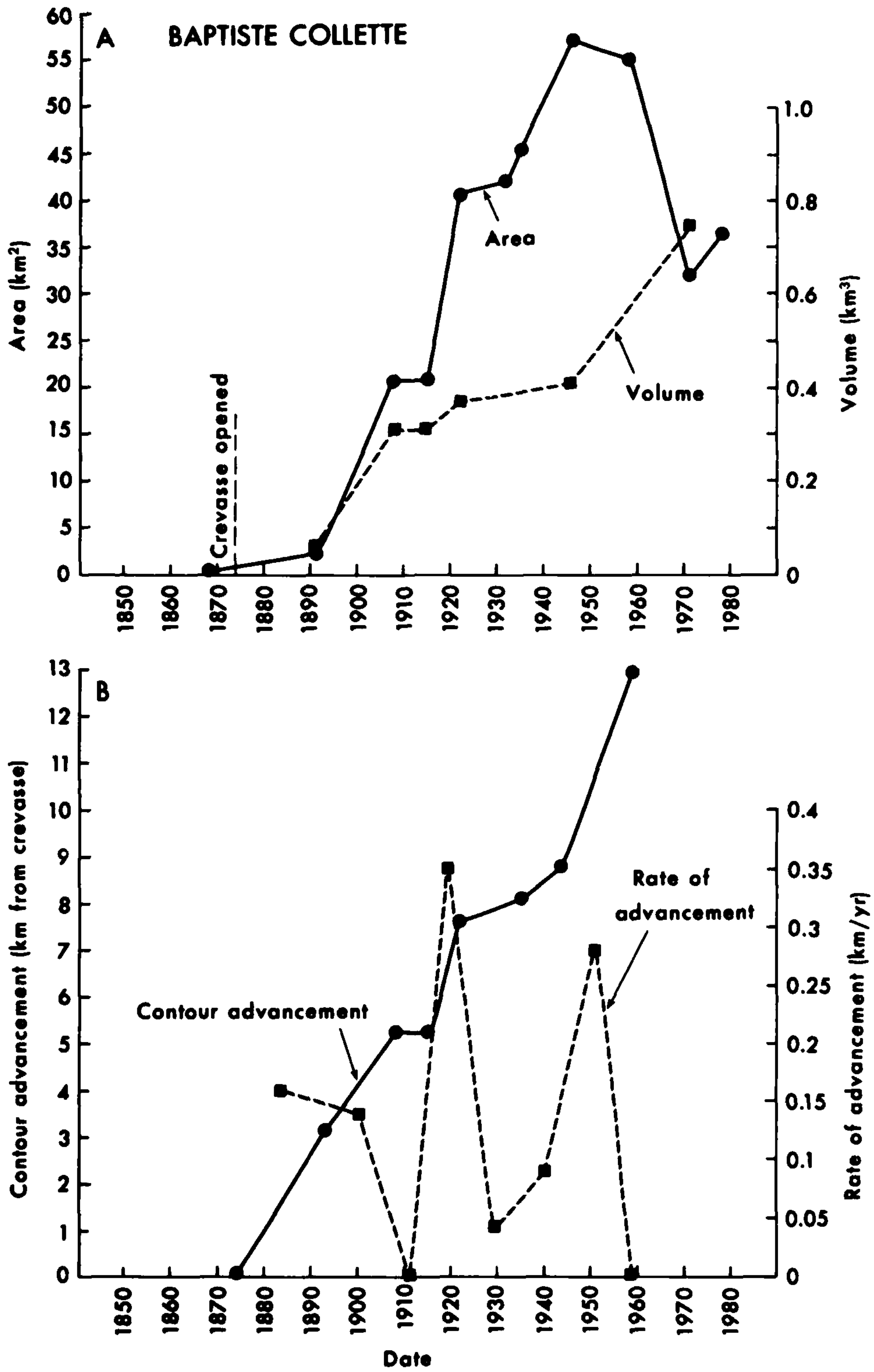

Figure 19. Linear, areal, and volume growth curves for the Baptiste Collette subdelta

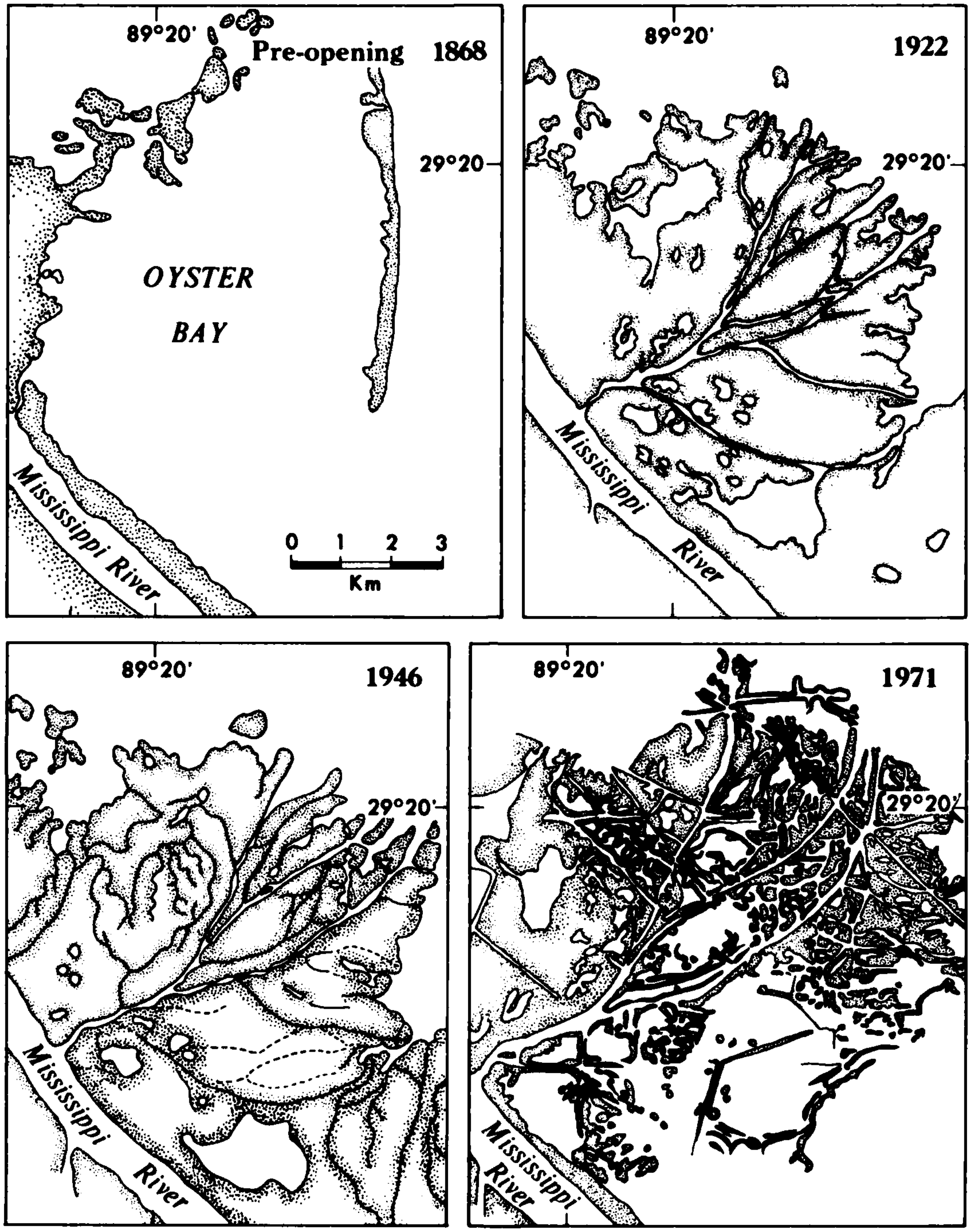

Figure 20. Sequential development of Baptiste Collette subdelta (constructed from C&GS and USGS charts)

69. A ditch that had been excavated by the daughters of Cubit, an oyster fisherman, to allow passage by boat between the Mississippi River and Bay Rondo, was immediately responsible for the crevasse break. According to Morgan (1977), the ditch was cut through natural levee that was no more than 120 m wide. With the flood of 1862, the ditch enlarged into a natural crevasse opening, and by 1868 the crevasse was 740 m wide. The opening had increased to a width of 840 m by 1875, then to 990 m by 1898; depth decreased from 40 m to 22 m during the same time period. Planimetric and bathymetric data compiled by Welder (1959) showed that as of 1952 the crevasse had remained over 900 m wide but had shoaled to a depth of 10 m.

70. Although the crevasse system evolved in only a few years' time, subaerial growth was sluggish as the deep receiving basin was filling subaqueously with sediments. A period of rapid growth (6.3 km^2/yr) began in 1891 and continued to 1905 (Figure 21A). During this 14-year period 88.3 km^2 of subaerial land were added to the Cubits Gap subdelta. By 1905 the passes were over 10 km long and were prograding at an average rate of 0.6 km/yr. Modest rates of growth (1.7 km^2/yr) prevailed to 1946, when the subdelta reached its maximum subaerial extent of 193.1 km^2. Unlike the Baptiste Collette and Garden Island Bay subdeltas, the Cubits Gap subdelta never stabilized, but entered a rapid destructional phase in 1946 (Figure 21A).

71. Between 1946 and 1953 subaerial land was lost at an average rate of 12.9 km^2/yr, the highest rate of any subdelta in the modern Mississippi River system. Figure 21B shows that between 1873 and 1922 the delta front was advancing at an average rate of nearly 0.5 km/yr, but that after 1922 the rate of advance diminished to 0.05 km^2/yr as the passes extended themselves to the point of inefficiency. Compaction and dewatering of underconsolidated sediment in the deep Rondo Bay receiving basin proceeded rapidly during the waning of the sediment delivery system. An important point to note is that CE discharge data reveal no systematic decrease in flow through the Cubits Gap crevasse since the early 1900's.

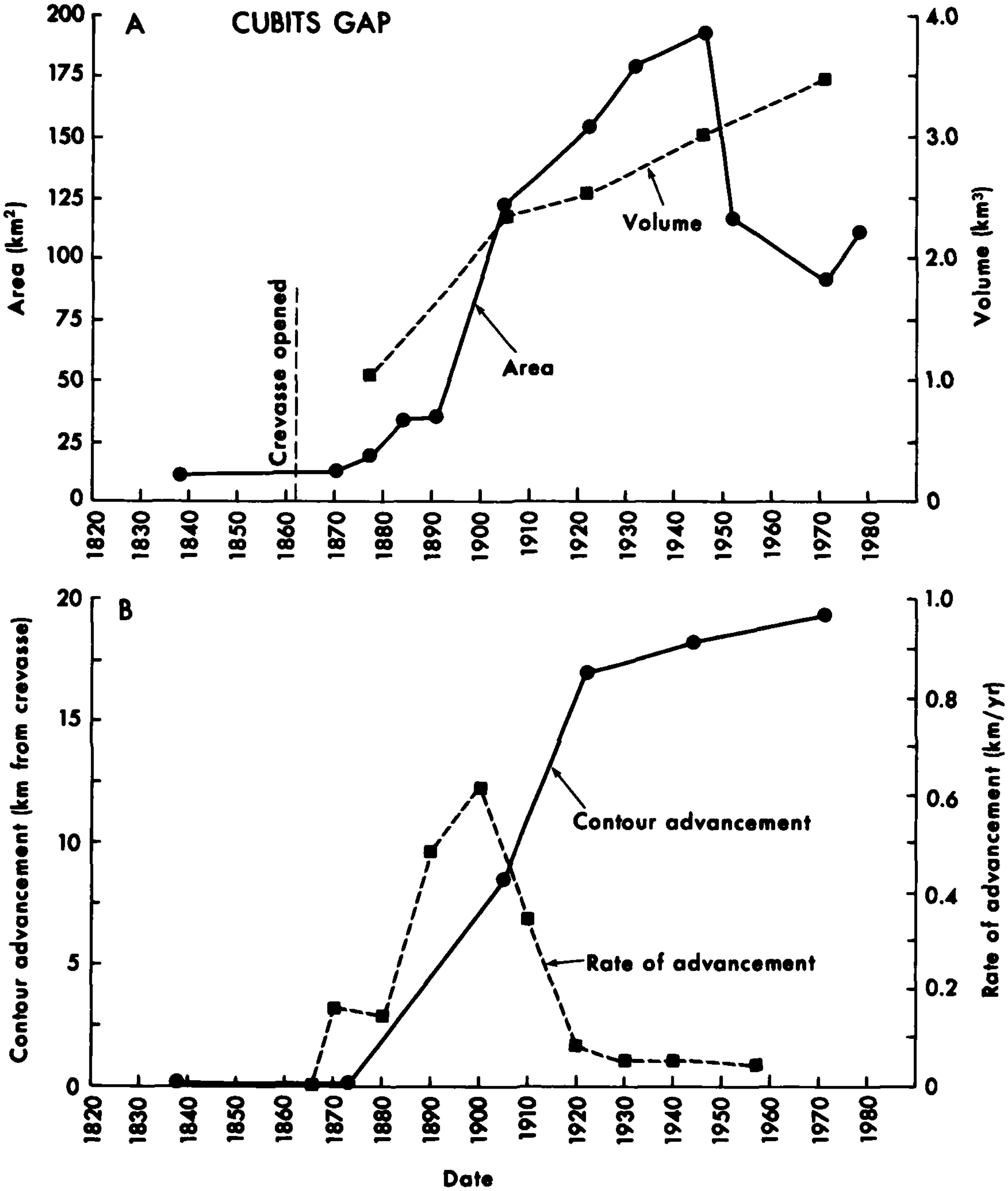

Figure 21. Linear, areal, and volume growth curves for the Cubits Gap subdelta

72. Figure 22 shows the sequential development of Cubits Gap subdelta, beginning with the Talcott survey of 1838. The survey of

1884, characterized by a primary channel separating the delta into two halves, looks remarkably like the present-day Lower Atchafalaya River Delta oriented approximately 160 degrees counterclockwise. The 1946 map shows additional subaerial land but some deterioration as well. By 1971 the main passes had deteriorated to the point where they could be recognized only by their natural levees. The typical pattern of deterioration is one of small water bodies reverting to larger bays. Of particular interest is the fact that major subsidence occurs in the oldest part of the delta.

73. The volume of the Cubits Gap subdelta was the largest of any Mississippi River subdelta. Average rate of growth was 0.026 km^3/yr, or three times that of the Baptiste Collette subdelta. Total volume fill as of 1971 was 3.5 km^3. There is no indication that rate of volume fill is related to rate of subaerial land growth (or deterioration). In fact, during the destructional phase (1946-1971) 0.42 km^3 of sediment was deposited in the bay. The Cubits Gap subdelta shows the best example of channel bifurcation and channel reuniting, which together form an intricate pattern of distributaries.

West Bay

74. The West Bay subdelta is the earliest subdelta for which accurate records are available, and a large number of borings have aided in interpreting its morphologic development (Coleman 1976). Initiated by a crevasse break in 1839, the West Bay complex developed rapidly to become the largest subaerial delta in the Mississippi River system. As an area of open water in the early 1830's, West Bay was approximately 7 m deep, situated in the lee of waves from the southeast and currents from the east (Figure 18). It is a particularly interesting subdelta in that sufficient data exist to document a loss of subaerial land prior to the crevasse opening and that a double peak in subaerial land is prominent during the period of stabilization. Further, some evidence is available to indicate that discharge through the crevasse has increased slightly since the early 1900's.

75. Prior to 1839, West Bay was connected to the Mississippi River by Wilder's Bayou; a lock allowed passage of shallow-draft vessels

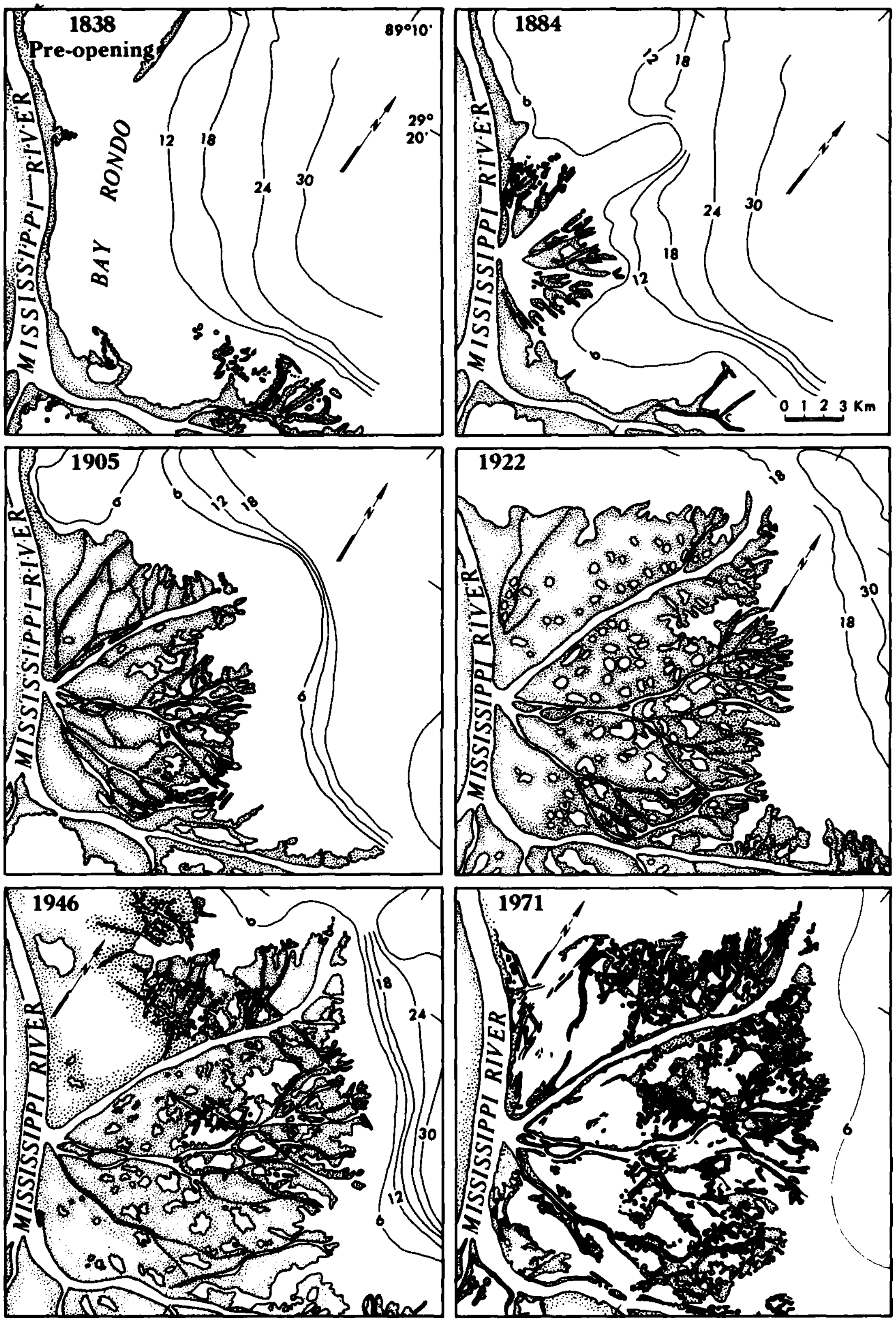

Figure 22. Sequential development of Cubits Gap subdelta (constructed from C&GS and USGS charts)

between the river and bay (Morgan 1977). During flood stage of 1839, the lock was destroyed and Wilder's Bayou became a crevasse known as The Jump. Enlargement of the crevasse took place quickly as a result of the creation of an enormous gradient advantage (5.6 m/km at flood stage through the crevasse versus 0.004 m/km at flood stage through the passes; Morgan 1977). By 1840 the crevasse was 400 m wide and 18 m deep. Scour from strong currents dominated near the crevasse, but rapid subaqueous sedimentation dominated in the bay. Within 6 years new land was developing at a rate unequaled by any of the other Mississippi River subdeltas (7.0 km^2/yr).

76. The first accurate map following the crevasse opening was produced in 1845 and showed 44.0 km^2 of subaerial land (Figure 23A). By 1875, 254.2 km^2 of land had formed, extending 17.4 km into West Bay. Approximately 86 percent of the total subaerial delta developed between 1845 and 1875. In 1875 the first signs of deterioration appeared, and subaerial land diminished until 1905 (Figure 23A). A sharp reversal in deterioration occurred in 1905, and a new pulse of growth added an additional 71.4 km^2. Deterioration began again in 1932 (average of 4.1 km^2/yr) and continued until a second pulse of sediments added 17.3 km^2 between 1971 and 1978. With one minor exception, linear growth continued throughout both cycles of subaerial growth and deterioration in the West Bay subdelta (Figure 23B).

77. Development of the West Bay subdelta is shown diagrammatically in Figure 24. Early in the subaerial growth (1845) flow was divided through four main channels. By the early 1900's two of these channels had completely sealed and two remained partly open. Flow was concentrated down Grand Pass, the largest of the distributaries. Deterioration in 1922 was causing small ponds to open, primarily at the mouth of Grand Pass. The large number of abandoned channels can be recognized as solid lines detached from the active channel system. The western shoreline remained smooth and regular as a result of sheltering from marine processes. Subsidence resulted in the loss of the southern half of the West Bay subdelta by 1978.

78. Estimates of volume fill show, as in the case of the other

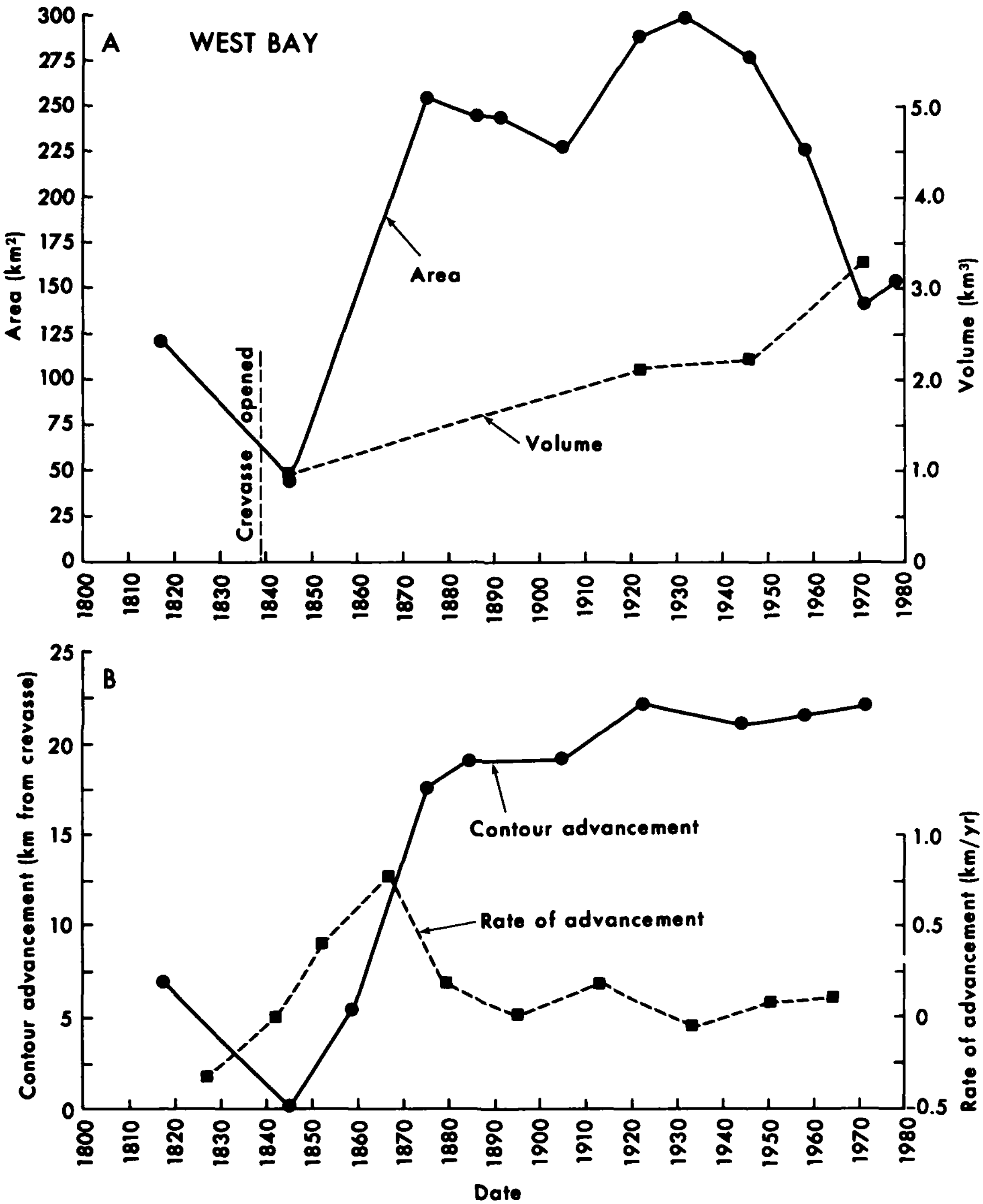

Figure 23. Linear, areal, and volume curves for the West Bay subdelta

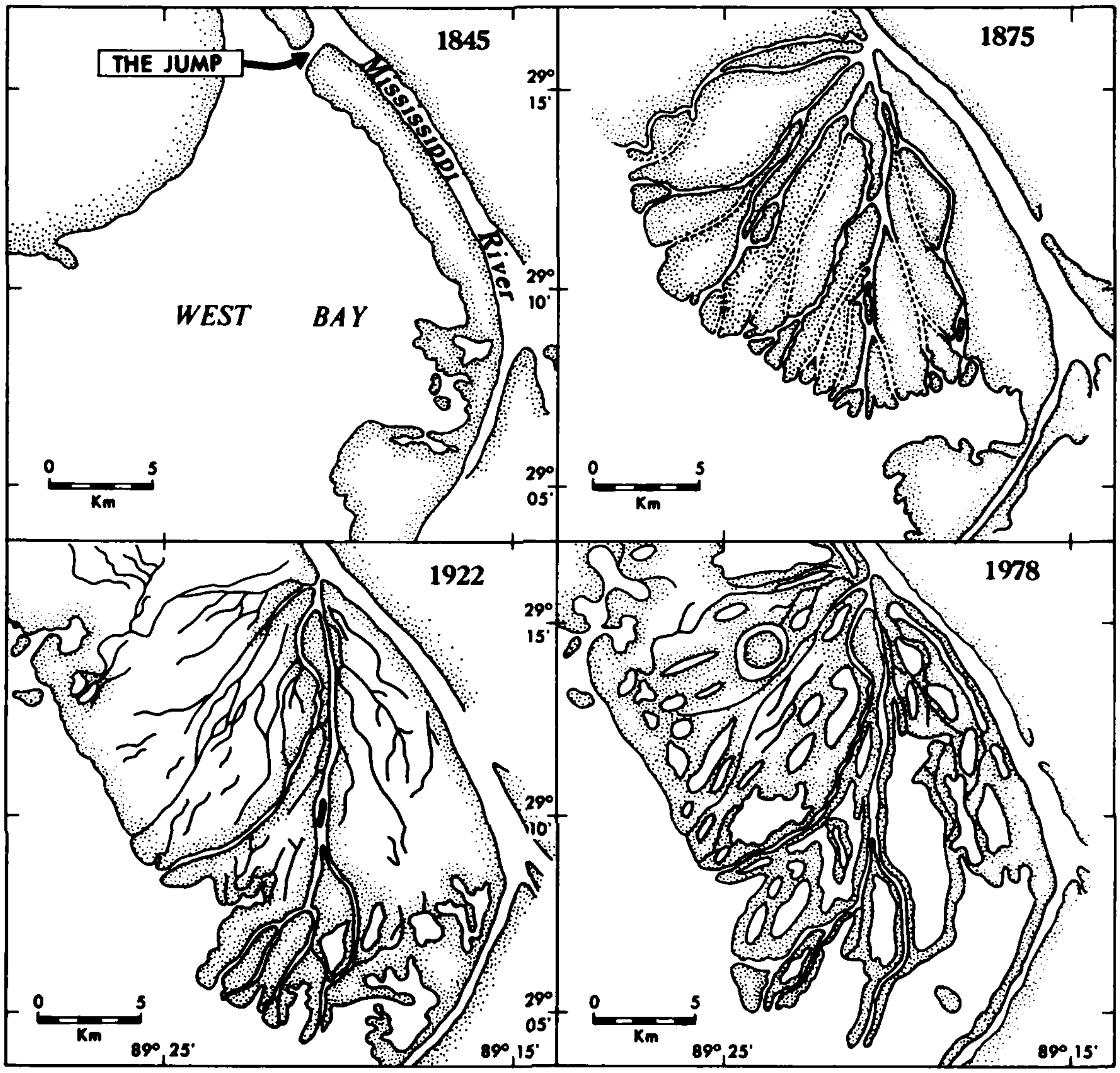

Figure 24. Sequential development of the West Bay subdelta (constructed from C&GS charts and aerial photographs)

subdeltas, a continuous input of sediments into the bay throughout the entire life cycle. The maximum rate of volume growth was 0.044 km^3/yr; total volume was 3.3 km^3. According to Coleman (1976), at least three complete cycles of progradation and abandonment have occurred in the area of the present West Bay subdelta.

Garden Island Bay

79. The Garden Island Bay subdelta, utilizing approximately 4

percent of total flow from the Mississippi River, developed a subaerial land mass that was twice the size of the Baptiste Collette (Figure 18). Building to the southeast between Pass a Loutre and South Pass, it filled the shallow (< 4 m) Garden Island Bay between 1891 and 1922. The life cycle of this subdelta has been the shortest of the four Mississippi River subdeltas; unless man intervenes, the Garden Island Bay subdelta will revert to open water within 25 years.

80. Details of the early crevasse system that initiated subdelta growth, summarized by Morgan from USACOE (1898) and Dent (1921), are provided below. In 1872 the location of the Pass a Loutre crevasse leading into Garden Island Bay was marked by a ditch 1 m wide and 200 m long. The ditch widened rapidly beginning in January 1891 as a result of natural processes, and by July 1891 the crevasse was 260 m wide and had reached a depth of 7.5 m. Attempts to close the developing crevasse system were unsuccessful, and by August 1892 the crevasse was 500 m wide. Within 1 year, July 1893, the channel had extended 1000 m into Garden Island Bay and was beyond artificial control. The crevasse had widened to 680 m by November 1896, and the first subaerial land was recorded in 1903. Between 1903 and the survey of 1914 subaerial deposits extended 10.8 km into the bay (Figure 25).

81. The sharpest subaerial growth occurred between 1914 and 1922 at an average rate of 6.9 km^2/yr. The highest point on the growth curve was reached in 1922, only 31 years after the crevasse opened (Figure 25A). During the ensuing 24 years (1922-1946) an overall balance between sedimentation and subsidence led to a period of stabilization characterized by a slight loss in subaerial land but a slight gain in linear contour advancement. Rapid deterioration began in 1946, averaging 2.0 km^2/yr between 1946 and 1971. As in the case of the other three subdeltas, a substantial gain in subaerial land was recorded between 1971 and 1978 (Figure 25A).

82. Figure 26 shows the appearance of Garden Island Bay between 1838 and 1971. An interesting observation is that 1922 marks the maximum subaerial growth (Figure 25A), yet deltaic sediments in 1971 extended over a larger area and showed additional growth; as the distal subaerial

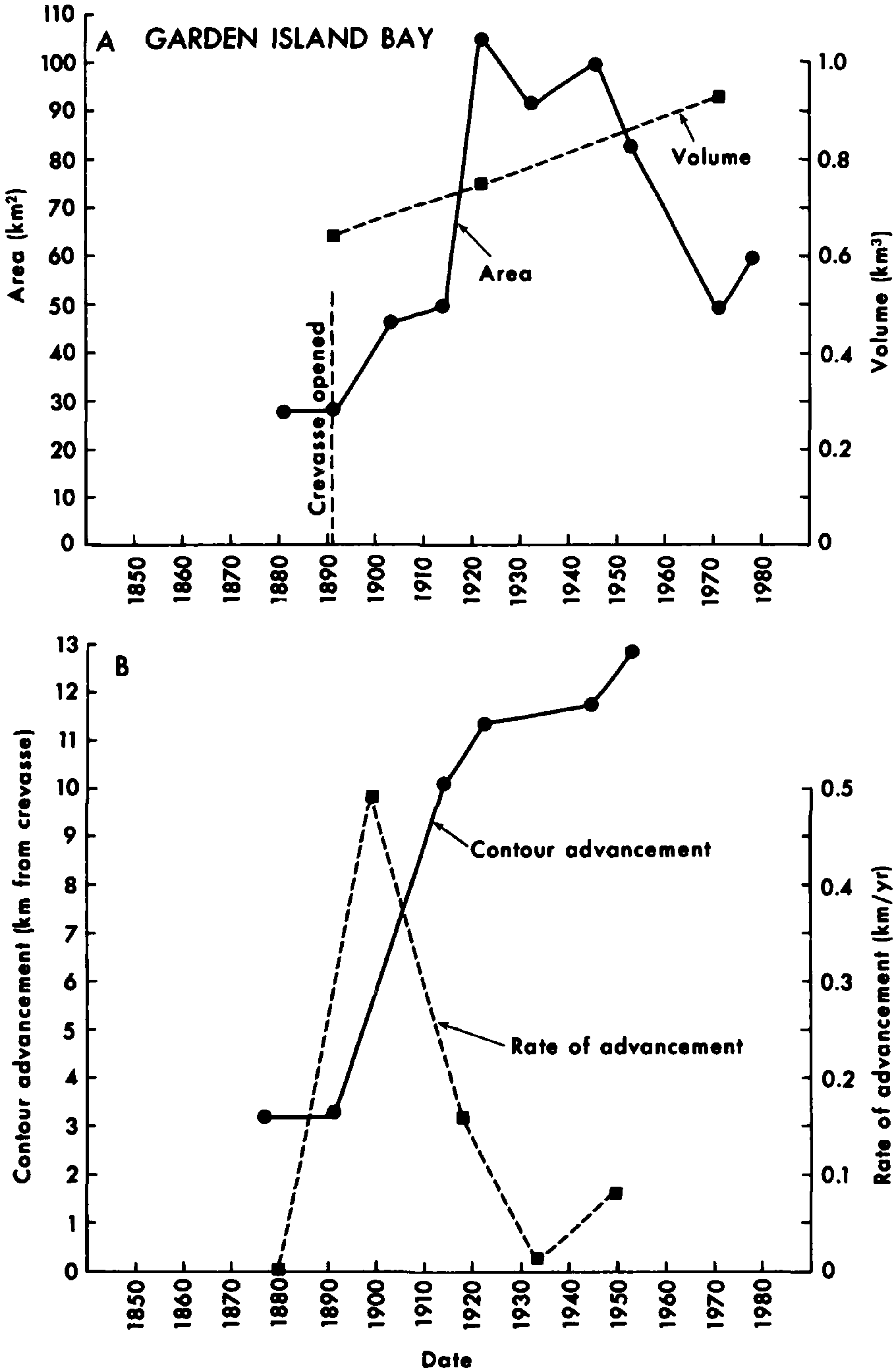

Figure 25. Linear, areal, and volume curves for the Garden Island Bay subdelta

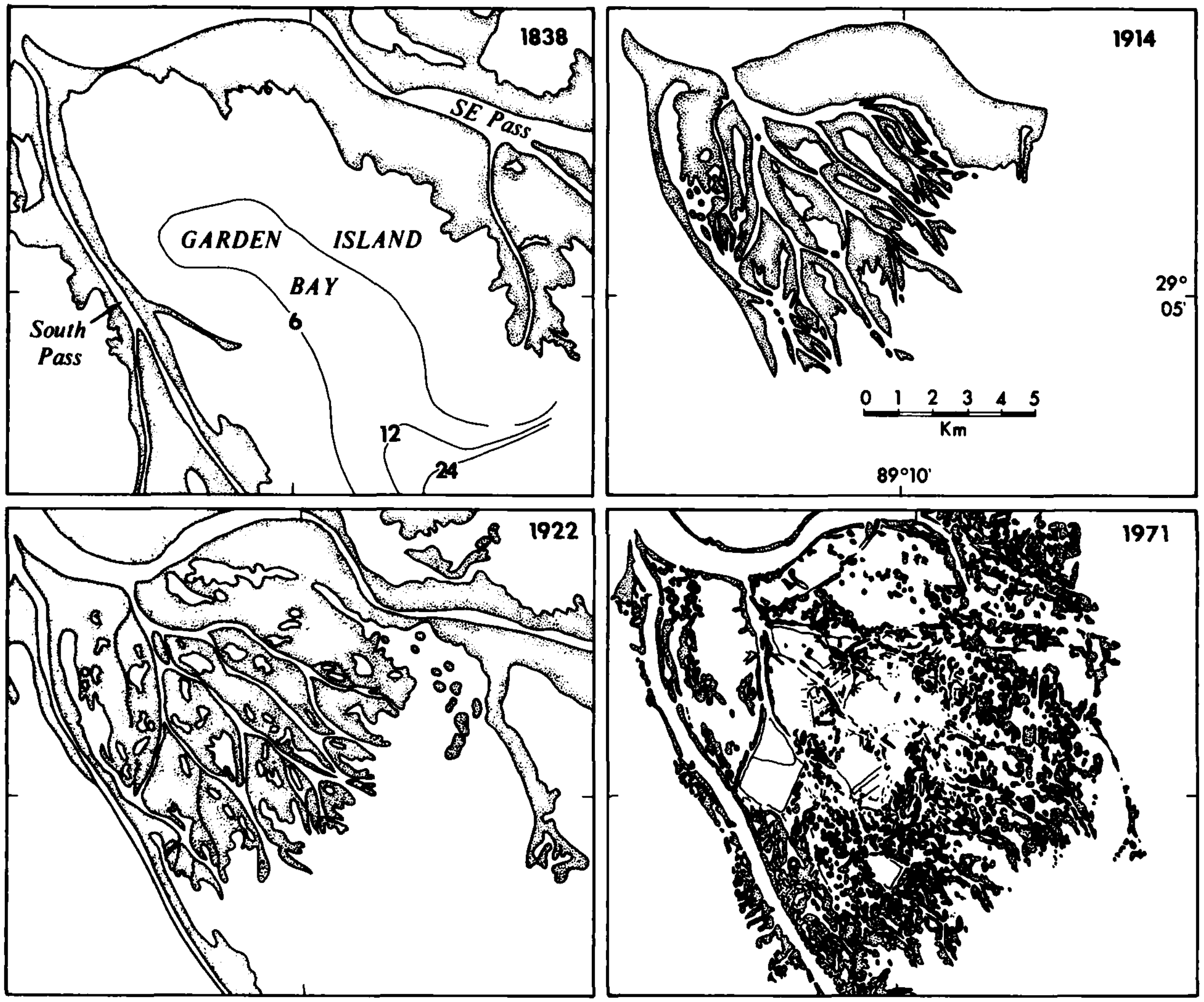

Figure 26. Sequential development of the Garden Island Bay subdelta (constructed from Mississippi River Commission files, USGS and C&GS charts)

delta continued to grow, the proximal subaerial delta reverted to open water through rapid subsidence. The rate of volume fill, based on data from three surveys, shows a steady increase at 0.004 km^3/yr from 1891 to 1971 (Figure 25B). Linear growth rates were highest immediately following the crevasse break (0.42 km/yr up to 1914) but began to diminish as the delta filled out subaerially between 1914 and 1922.

Summary of Mississippi River subdeltas

83. Results of the map analysis, together with an extensive review of published and unpublished reports, indicate that five features are common to the Mississippi River subdeltas: (a) initiation of growth by a crevasse or break in the natural levee system; (b) a well-defined life cycle that includes both growth and deterioration; (c) a life of approximately 115 to 175 years; (d) continuous infilling and linear growth throughout the destructional phase of the subaerial life cycle; and (e) a new pulse of subaerial growth between the surveys of 1971 and 1978.

84. Although initiation of growth in each of the Mississippi River subdeltas was a result of a break that took riverflow over and through previously deposited natural levee sediments, this process was aided by man's activities in three of the subdeltas. Artificial cuts in Cubits Gap, West Bay, and Garden Island Bay enhanced the natural crevasse process by providing a weak link in the levee system. A particularly dramatic example is the artificial cut that led to the Cubits Gap crevasse in 1862. However, historical records suggest that the breaks occurred during rising floodwaters and that once initiated, they were then beyond the control of man. The general pattern in the crevasse is one of initial scour that forms a channel 5-40 m deep which, after 10-30 years, begins to shoal. Whereas scour occurs through the crevasse break, large volumes of sediments are carried into the interdistributary bays to provide a base for subaerial land. Subaerial land becomes established after repeated bifurcations and the development of an organized channel pattern.

85. Figure 27 shows on a single plot the cyclic nature of the four Mississippi River subdeltas; each cycle consisted of growth followed

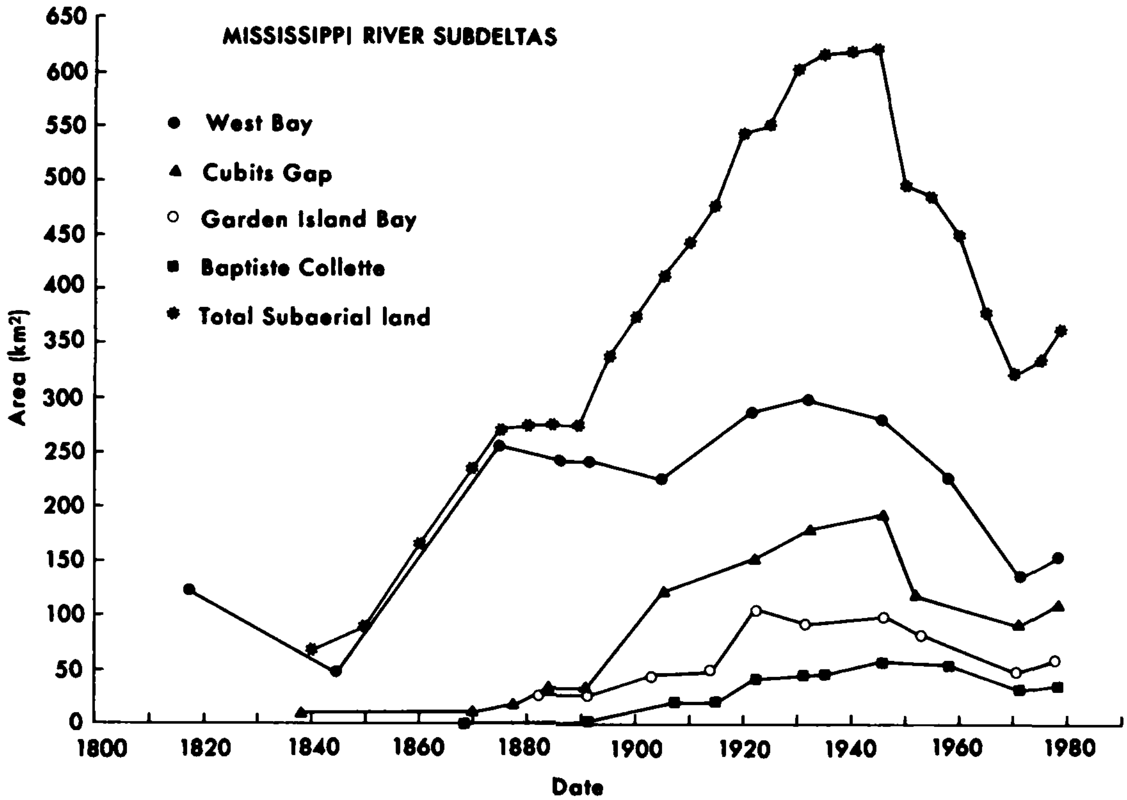

Figure 27. Composite subaerial growth curve, Mississippi River subdeltas. Total subaerial land determined from averages at 5-year intervals

by deterioration. Two of the subdeltas, Baptiste Collette and Garden Island Bay, showed a period of stabilization of 12 to 24 years, and the West Bay subdelta displayed a double peak spanning 57 years. The total subaerial land from these four subdeltas, averaged at 5-year intervals, shows 622.5 km^2 at the peak of development. In 1945 the onset of deterioration began abruptly.

86. The life cycle of the Mississippi River subdeltas is on the order of 115-175 years (Table 3). Extending to the X-axis, the present trends in deterioration indicate that subaerial land should remain for another 17-34 years. These projections were carried out ignoring the renewed growth in each subdelta between 1971 and 1978. Present trends suggest that these growth pulses, the first in some 50 years, are simply a perturbation on the overall destructional phase. Although

subaerial growth did not begin until 10-15 years after the crevasses opened, the life of each of the subdeltas was initiated at the time sediment was introduced to the interdistributary bay. Thus the first 10-15 years were a period of subaqueous expansion. Whereas no systematic pattern between rate of growth and rate of deterioration could be detected, once the primary distributaries had developed, progradation reached its maximum (1.1-7.0 km^2/yr). Average rates of subaerial growth and deterioration, based on data plotted in Figure 27, were 2.1 km^2/yr and 2.6 km^2/yr, respectively.

87. The plots in Figures 19, 21, 23, and 25, together with data summarized in Table 3, show that throughout the full cycle of growth and deterioration, total volume and the linear growth of subdelta sediments continue to increase. In every case, the maximum rate of contour advancement is during the early part of subaerial growth and lasts 25 to 30 years. As channels become overextended and the discharge gradient is lost or bifurcations cause development of too many outlets, rapid deterioration occurs; the 1959 discharge gradients of 0.1-0.05 m/km (Table 3) were insufficient to build subaerial land. Deceleration of contour advancement ordinarily occurs at or before the peak of subaerial land. Data were insufficient to correlate rate of volume fill with rate of subaerial growth; however, as a point of interest, the rate of volume fill in two of the subdeltas (Baptiste Collette and West Bay) increased during the destructional phase.

Atchafalaya River Deltas

88. Results of the LANDSAT analysis provide the rates and patterns of growth for deltas in Atchafalaya Bay since subaerial emergence in 1973. Figure 28 shows a plot of subaerial land in the Wax Lake and Lower Atchafalaya River deltas, beginning with the flood year 1972-1973. Each data point represents the amount of subaerial land at mean sea level for flood years as defined in Figure 7. Although data are plotted at midyear positions in Figure 28, they should be considered as averages for the respective flood years.

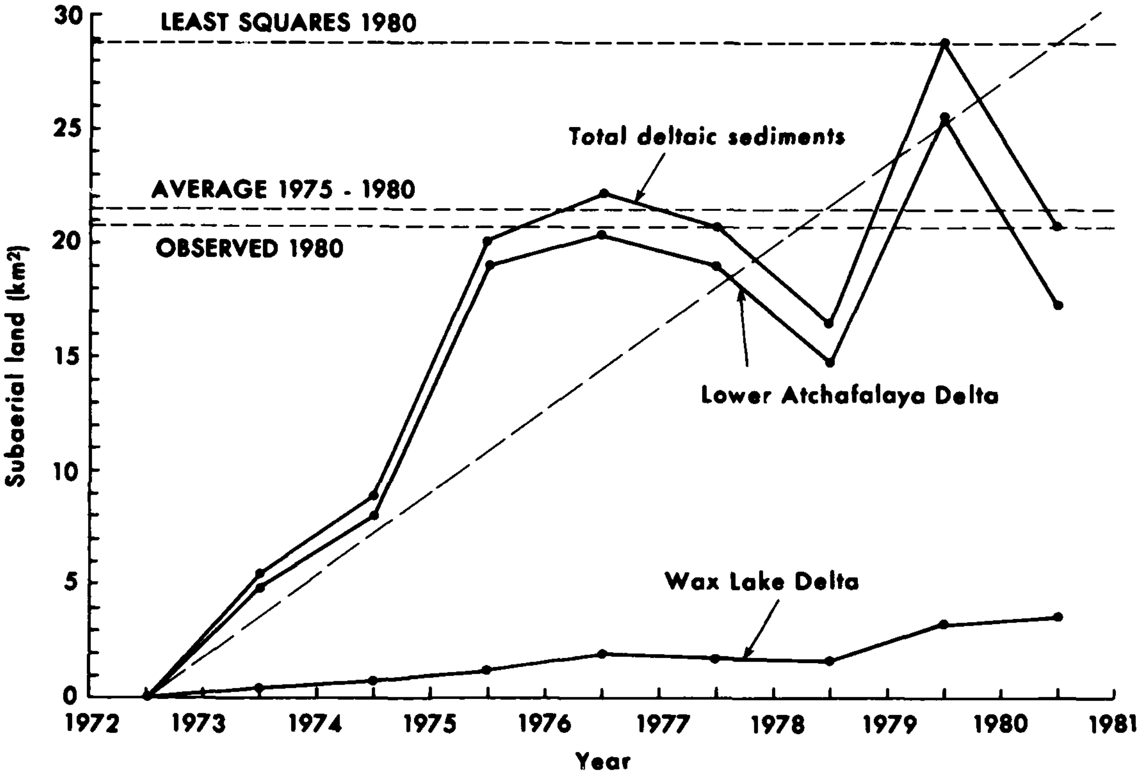

Figure 28. Growth curves for total subaerial land, Lower Atchafalaya River Outlet and Wax Lake Outlet. Estimates for average subaerial land for 1980-1981 (dashed lines) taken from least squares best fit to all data, average for 1975-1980 flood years, and observed land in 1980 to 1981 flood year

89. The most obvious observation is that growth of total subaerial land has been episodic. Major pulses of sedimentation occurred for the first 4 years after the 1972-1973 flood year and again during the 1979-1980 flood year. Subaerial land was lost between the 1976-1977 and 1978-1979 flood years and again following the 1979-1980 flood year. Maximum rate of growth occurred during flood year 1979-1980 (12.3 km^2/yr), and maximum rate of land loss occurred the following year (7.9 km^2/yr).

90. If the curve for the total growth in Atchafalaya Bay is divided into its two components, the Wax Lake and Lower Atchafalaya River Deltas, then it becomes evident that the Lower Atchafalaya River Delta controls the subaerial growth rates and that the Wax Lake Delta behaves in a

slightly different fashion. At present the Wax Lake Delta represents 17 percent of subaerial land observed in the 1980-1981 flood year and 10 percent of subaerial land if averaged over the last 6 years. The Wax Lake Delta has never undergone substantial loss of subaerial land and has continued to grow throughout the period of rapid land loss in the Lower Atchafalaya River Delta in 1980-1981. Relative to its size, the Wax Lake Delta is now growing faster than the Lower Atchafalaya River Delta. Within the Lower Atchafalaya River Delta, 70 percent of the subaerial land is west of the navigation channel when observed at mean sea level.

91. Three estimates for the representative amount of land in Atchafalaya Bay as of the 1980 base year are shown in Figure 28 as dashed lines. The first is simply the amount of land observed from LANDSAT images during the 1980-1981 flood year (20.8 km^2). The second estimate is an average for the last 6 years beginning in 1975 (21.5 km^2). The third value is from a least squares best fit, forced through the origin (1972-1973 flood year), that indicates a total of 28.8 km^2. Based on these three estimates, average rates of growth are 2.6, 2.7, and 3.6 km^2/yr for the observed, averaged, and least squares determinations, respectively.

92. Aerial photographs and photomosaics show that the deltas have grown by producing parabolic lobes of silt and fine sand that radiate out from the network of branching distributaries (Figure 29). The delta lobes have evolved from shallow distributary-mouth bar sands that achieved an elevation above mean sea level during major floods. The pattern of development shows at least six levels of bifurcation since the first major split in the main channel before the emergence of subaerial land in 1973. During the 1974 flood, the eastern branch began to bifurcate, thus producing second- and third-order distributaries. This process continued in 1975 and again in 1979 as the delta lobes extended themselves seaward. Rates of contour advancement have ranged from 0 to 0.40 km/yr. On the western branch of the main channel, the lower navigation channel, spoil mounds were redistributed by floodwaters to produce similar patterns of channels and emergent delta lobes.

Figure 29. Photomosaic of Lower Atchafalaya River Delta, 12 October 1976, showing levels of bifurcation

PART IV: DISCUSSION

93. Results of the generic analysis indicate that deltas throughout the world which are similar to the deltas in Atchafalaya Bay (a) display a life cycle that includes both growth and deterioration, (b) develop by building lobes or subdeltas through the process of crevassing, and (c) grow primarily by channel extension and bifurcation, which includes the formation and development of a midchannel bar.

The Life Cycle

94. The deltas considered in this study have life cycles that range in duration from a low of 100 years in Lake Maracaibo to a high of 1000-3000 years in the subdeltas of the Danube River. The best examples of the life cycle are given by the Mississippi River subdeltas, as summarized below. During the progradational phase of development in a subdelta of the Mississippi River system, active growth will commence after crevassing takes place (Figure 30) but, as Figures 19-26 show, not at a constant rate. An initial break in a natural distributary levee during flood stage will produce deposits of coarse sediment in the vicinity of the break. Fine-grained sediments infill the bay area, building up a platform for further channel progradation. At some point in the subaqueous infilling process, channel development by a well-organized pattern of bifurcations takes place, and both progradation and areal extent of the subaerial delta will increase rapidly. As more and more channels form and begin to function, progradation rate and new land addition will diminish. Finally, land gain and land loss (by subsidence and sea-level rise) will reach a point of balance. Marsh growth that typically covers the bay-fill sediments will attempt to keep pace with erosion and compaction. Eventually, the marsh can no longer maintain its growth rate to keep up with processes of subsidence, and the marsh cover will begin to open into many small lakes and bays (Figure 31). Inundation by marine waters will then cause the complex to revert to a shallow marine bay environment, thus completing one infilling and abandonment cycle.

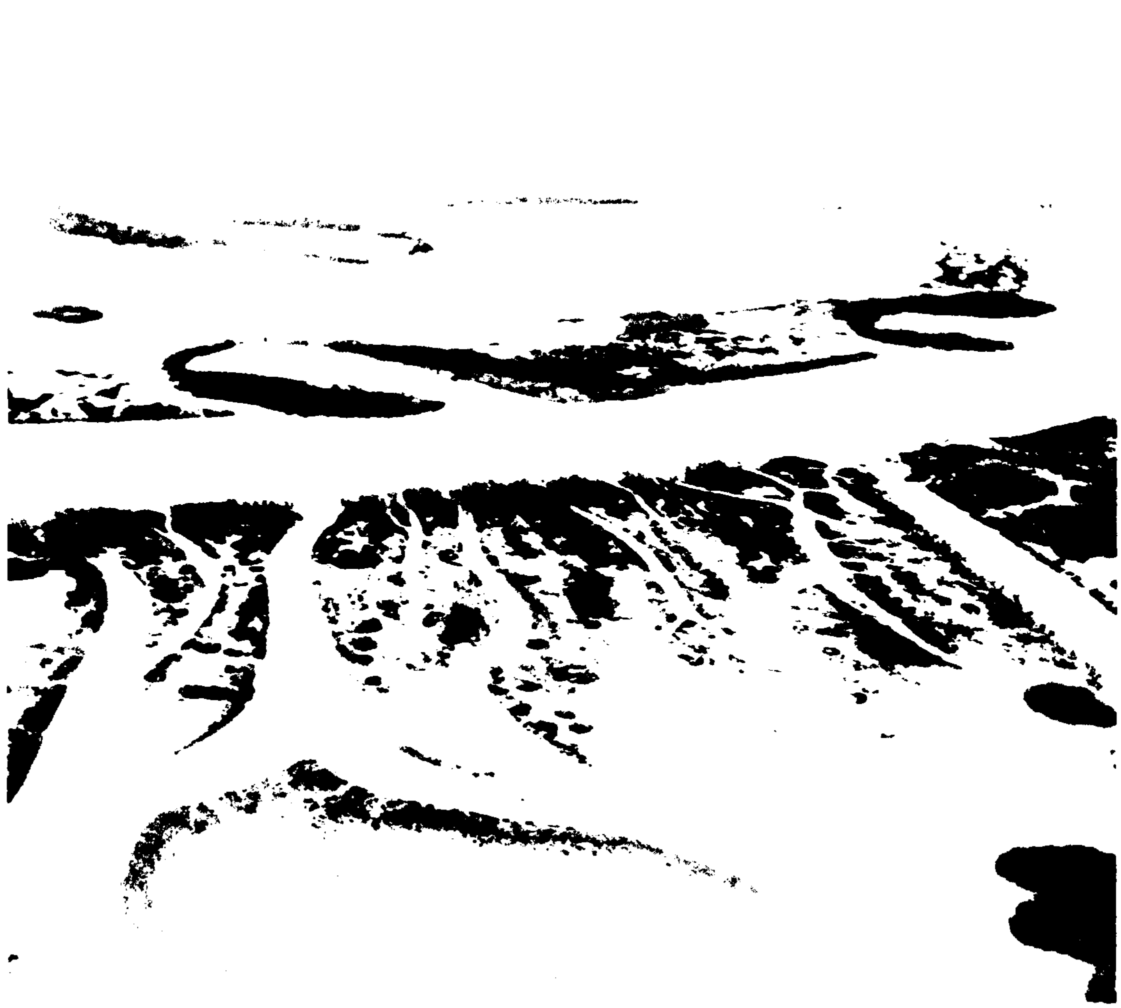

Figure 30. Crevasse channels extending across natural levees into an interdistributary bay, Mississippi River Delta. Note the formation of a large delta lobe at the point of bifurcation on one of the crevasses

95. Every delta that was examined in the generic analysis grew by developing lobate features that rapidly gained subaerial exposure and, with one exception (Catatumbo Delta), were the result of the formation of crevasse splays. The formation of broad parabolic delta lobes appears to be restricted to deltas such as the Atchafalaya River delta that are building into shallow receiving basins. Upstream of their modern-day deltas, most of the rivers had undergone natural diversions during historic times: the Trinity River switched to the east side of the Trinity Valley 500-800 years ago; the Danube River shifted from the Gheorghe to the Sulina and Chilia distributaries during the last

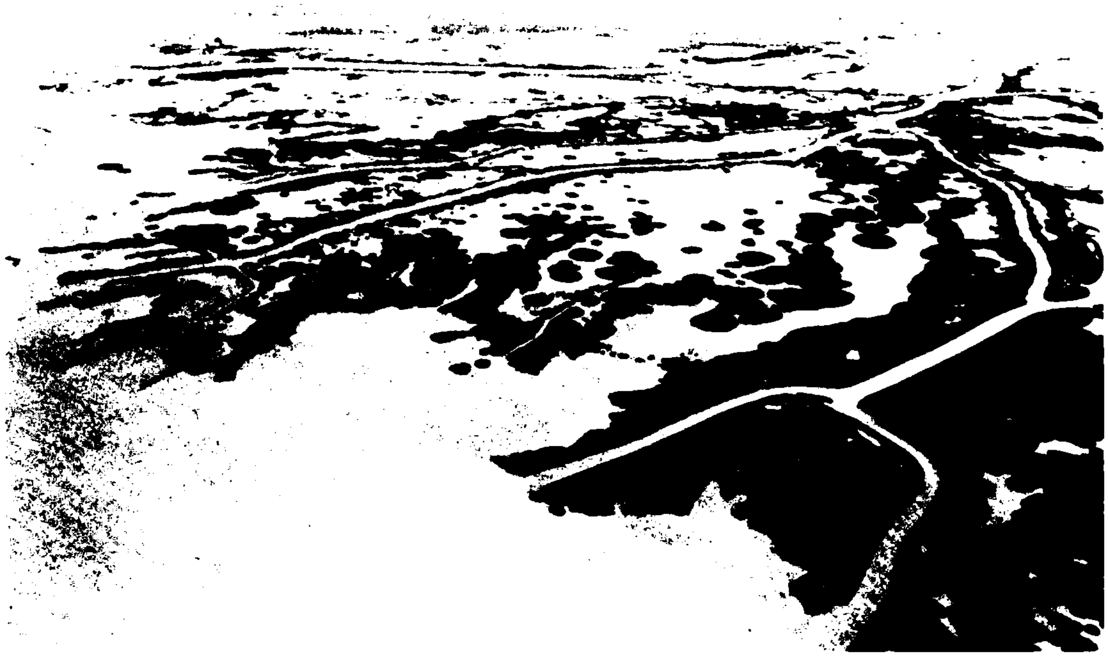

Figure 31. Deterioration of marsh in the Cubits Gap subdelta. Life expectancy of the subdelta that remains is less than 25 years

6000 years; and the Catatumbo Delta formed after flow shifted from the Rio Bravo and Rio Bobo channels 70 km upstream of the present delta. Moreover, subdeltas have been stacked vertically through time and can coalesce to form continuous land of enormous proportions.

96. The loss of subaerial land in West Bay for at least 22 years prior to the 1839 crevasse opening (Figure 23) is an example of the repetitive nature of subdeltas. Subaerial land in West Bay in the early 1800s was most likely a remnant of a previous subdelta in its final stages of deterioration. Examples of the merging of individual lobes are shown best by the Colorado Delta, where four lobes coalesced between 1929 and 1941 (Figure 10); the Cubits Gap and Baptiste Collette subdeltas, which came together between 1922 and 1932 (Figures 19-22); and the Danube

Delta, where five lobes have produced 5000 km^2 of subaerial land in 6000 years (Figure 17). Thus what one sees at an instant in time may be the result of many sediment pulses or depositional events. The implication to the two Atchafalaya River deltas is that the configuration of land in the future may not be a simple seaward extension of each delta as we see it today.

97. Life cycles of the deltas examined in this analysis appear to be independent of river discharge alone but highly dependent on a complicated relationship between river and sediment discharge, development of distributary channels, sea level rise, subsidence, and man's activities. This relationship cannot be quantified but can be easily understood in a qualitative fashion. In a delta with very rapid subsidence, as in any of the four Mississippi River subdeltas, the cessation of sediment delivery as a result of artificial levees, a natural diversion, or the sealing of a crevasse opening will cause (initiate) deterioration within perhaps 10 years. Further, if subsidence is on the order of 1 cm/yr, then the delta may eventually deteriorate even without a major change in main stem discharge or in cross-sectional area of the crevasse.

98. The primary reason for natural deterioration when subsidence rates are moderate to high is the loss of critical stream gradient at a time when small channels are forming a complex and inefficient network for delivering sediments. This appears to be part of the reason for deterioration of the Guadalupe Delta, which began to lose land at least 50 years ago. The Guadalupe Delta is an example of a system that has been relatively unaltered by man and that has maintained a continuous river discharge. Active growth ceased over 100 years ago, well before the first flood-control structures were built in 1954. Two-thirds of the sediments are now going into the Traylor Cut subdelta, an area that represents only 2 percent of the total subaerial delta. Although it is unknown whether or not this artificial cut initiated erosion on much of the delta, it is known that the delta is eroding and prograding simultaneously.

99. The Colorado and Trinity Deltas are both deteriorating, but

both have been altered substantially by man. The Colorado Delta is an excellent example of the disruption in growth behind a barrier after the navigation channel was leveed and the barrier was breached. Sediment began discharging offshore in 1936 when a channel was cut through Matagorda Peninsula and ceased to discharge into the bay when levees were constructed in 1941. Sediment discharge has been insufficient to build a new marine delta seaward of Matagorda Peninsula. The Trinity Delta ceased to grow after it prograded across Trinity Bay and the navigation channel was dredged to redirect water to the southwest. As in the case of the Colorado Delta, sediment then began bypassing existing deltaic deposits for deeper water. The lack of open marine conditions will allow shoaling to continue in upper Trinity Bay, and small amounts of localized subaerial progradation will take place simultaneously with the overall process of deterioration.

100. Deterioration of the Mississippi River subdeltas has been the cause for much speculation in recent years. Construction of artificial levees and extension of the Balize Delta to the shelf edge are usually cited as reasons for the loss of subaerial land. However, artificial levees end upstream of the four active subdeltas and thus do not prevent sediments from entering the subdelta system.* Moreover, the Mississippi River Delta was approaching the shelf edge well before the abrupt onset of deterioration that began in 1945 (Figure 27). Attempts to explain loss of subaerial land by relating average discharge to the life cycles of subdeltas have proved somewhat disappointing. Figure 32 shows growth and deterioration of each subdelta, together with a composite of all subdeltas, and a superimposed 7-year moving average of river discharge (Vicksburg station). The overall behavior of the subdeltas can be correlated to river discharge in four instances.

101. First, the composite curve for all subdeltas indicates that the initiation of growth occurred during a period of high discharge from 1840 to 1852. However, this can be attributed almost entirely

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* Sills across the crevasse openings may prevent bed-load sediments from entering during low river stage but are probably ineffective during flood stage, when sands are carried in suspension and overbank flooding is common.

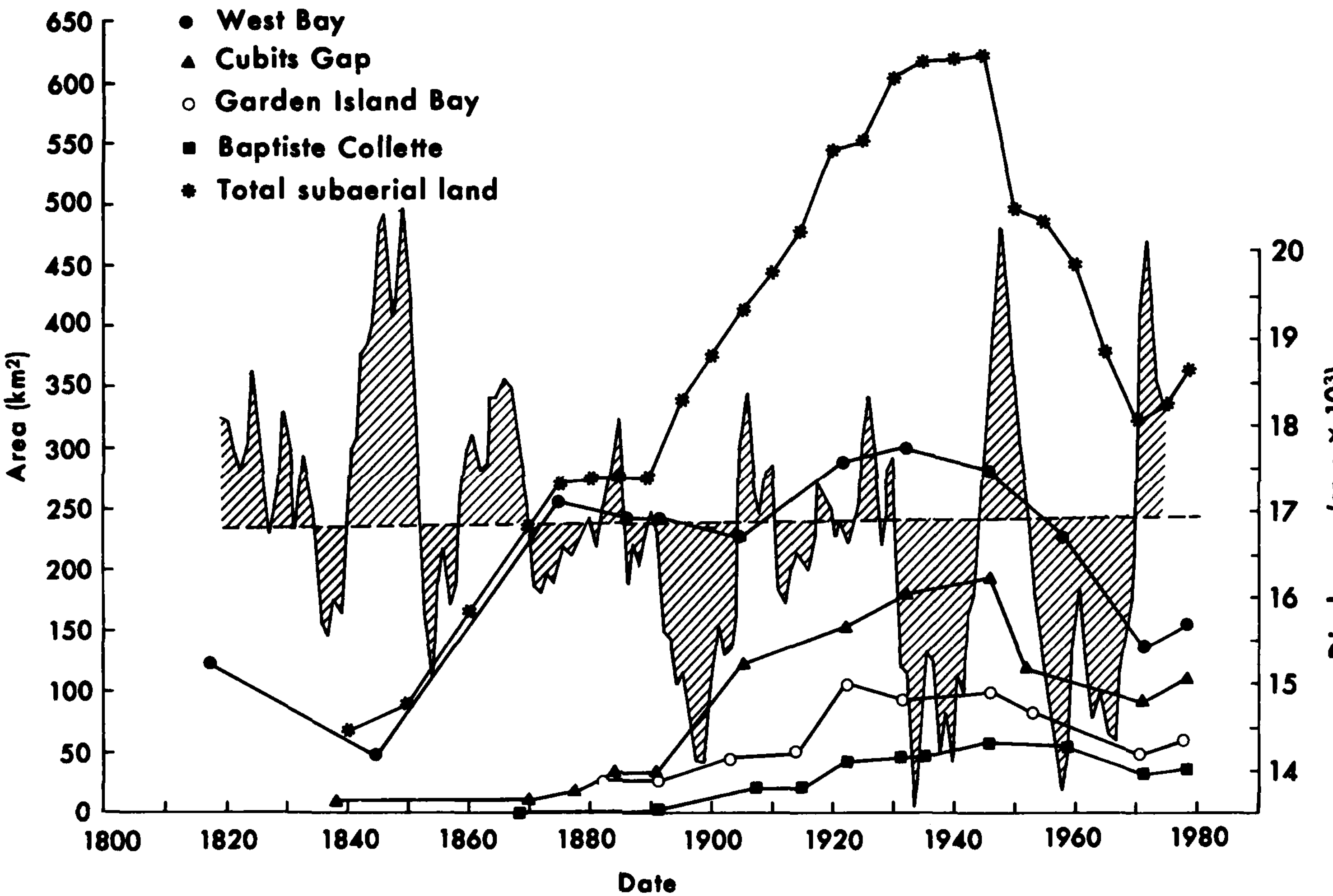


Figure 32. Composite and individual growth curves of the Mississippi River subdeltas showing their relationship to a 7-year moving average of Mississippi River discharge, 1917-1977, taken from the CE gaging station at Vicksburg

to growth of the large West Bay subdelta. Rapid growth continued during higher than average discharges between 1858 and 1870. Second, a period of stabilization between 1875 and 1890, again a reflection primarily of the West Bay growth, can be correlated reasonably well with the mildly fluctuating discharge patterns between 1870 and 1890. Rapid growth continued during a period of very low discharge from 1890 to 1905, precisely at a time when every subdelta except West Bay was becoming well established (West Bay was losing land). Third, the period of stabilization between 1930 and 1942 took place during very low discharges over the same time period. With the exception of high discharges between 1942 and 1951, the remainder of the deterioration curve until the late 1960's occurred during lower than average discharges. Fourth, the final pulse of sedimentation recorded on each of the individual subdeltas between 1971 and 1978 can be correlated with a renewed period of high discharges in the 1970's associated with major floods in 1973, 1974, and 1975.

102. The best overall explanation for deterioration of the subdeltas is a combination of three reasons. First, the Atchafalaya River has been taking progressively more discharge from the Mississippi River since the early 1900's. In 1900, 87 percent of the total flow below Old River went down the Mississippi River, whereas by 1950 flow below Old River had decreased to 70 percent. Second, dredging records show a fining of the bottom sediments in the Lower Mississippi River between 1932-1934 and the period after 1965 (Keown, Dardeau, and Causey 1980). Coarse sediment not reaching the delta is precisely the material needed for subaerial land. Third, the total volume of sediments that potentially make their way to the Mississippi River Delta is reported to have decreased by 41 percent since 1963 (Keown, Dardeau, and Causey 1980). Assuming the above numbers to be correct, the net effect since the early 1900's is 50 to 60 percent less sediment available for building new land in the Mississippi River subdeltas. However, the cause for abrupt deterioration of the composite curve in 1945 is still unexplained.

103. The role of subsidence in the process of rapid deterioration, whether or not man has modified the system, cannot be overemphasized.

Average rates of subsidence in South Louisiana range from 1 to 4 cm/yr (Kolb and Van Lopik 1958; Swanson and Thurlow 1973), mainly because of compaction and dewatering of rapidly deposited sediments that are no coarser than medium sands. Sea-level rise, often included under the heading "subsidence" because of the difficulty in separating the two, is considerably less important in the loss of subaerial land over such short time periods. Eustatic sea-level rise of 15-30 cm/century (Hicks and Crosby 1974) accounts for approximately 10 percent of the total subsidence rate.

104. The fact that the total volume of sediments in every subdelta has continued to increase irrespective of loss in subaerial land is certainly a direct result of subsidence. Assuming that reported subsidence rates of 1-4 cm/yr are reasonable, then 1.15-7.0 m of subsidence will occur during the life of a subdelta (115-175 years; Table 3). In most cases, the amount of subsidence over the life of a subdelta exceeds the depth of the receiving basin prior to the crevasse opening. Whereas sedimentation may not be sufficient to keep pace with subsidence, it nevertheless continues to fill the subdelta receiving basins as they slowly revert to open water. The increased rate of volume fill during subaerial deterioration of two of the subdeltas, Baptiste Collete and West Bay, was the result of a slight increase in crevasse discharge since the early 1900's (Table 3).

105. Rates of volume fill and depth of receiving basins are important because without this information it would be difficult to explain the size of the subdeltas relative to the percentage of total discharge through their crevasse openings. For example, the West Bay subdelta, with a discharge one-third to one-half that of the Cubits Gap subdelta, built by far the largest Mississippi River subdelta at the highest average and highest maximum rates of subaerial growth (Table 3). Total volume of the West Bay subdelta was only slightly less than that of the Cubits Gap subdelta (3.30 versus 3.50 km^3). However, the Cubits Gap subdelta was filling the deepest receiving basin at the highest average rate of sediment deposition (0.026 km^3/yr). Although Cubits Gap became the second largest subdelta, much of the sediment discharge throughout its life was being used for subaqueous sediment fill. Thus per unit time

low discharge can produce a large amount of subaerial land in a shallow receiving basin, high discharge may produce less land in a deep receiving basin, but neither situation will produce subaerial land unless sediments are retained in the receiving basin at rates sufficient to offset subsidence. The above example is relevant to the deltas in Atchafalaya Bay in that the receiving basin is very shallow, the percentage of incoming sediments is very high, yet the anticipated rate of subaerial land growth will be realized only if the rate of volume fill is also high.

The Atchafalaya River Deltas

106. Shlemon (1975) suggested that four transitional phases could be recognized in the life cycle of the Atchafalaya River deltas: (a) initial flocculation and shoreline accretion far removed from the locus of deposition; (b) 15-25 years of slow subaqueous growth; (c) rapid subaerial expansion; and (d) subsidence, compaction, and eventual deterioration. Even though the Atchafalaya River deltas are well into the third phase of the delta life cycle, growth associated with the first two phases is continuing. Shoreline accretion on the Louisiana Chenier Plain 100 km to the west is increasing (Wells and Kemp 1981; Wells and Roberts 1981), and slow subaqueous growth is evident in the distal northeast and southeast segments of Atchafalaya Bay.

107. Whereas 1973 marks the initiation of rapid subaerial growth in Atchafalaya Bay, the onset of subaqueous growth in 1952 should be considered as the equivalent to a crevasse break in a subdelta system. Although sediment discharge to the Atchafalaya Basin had been steadily rising since at least 1900, most of the sediment was fine and bypassed Atchafalaya Bay until Grand and Six Mile Lakes, to the north, reached a sediment-filled state in the mid-1900's. Using 1952 as the year for subaqueous birth, the Lower Atchafalaya River Delta at this writing is 30 years old and produced its first natural subaerial land 21 years after initial sedimentation. Figures 19-26 show that subaerial land in the Mississippi River subdeltas was first recorded 5-15 years after crevasse opening and that although the crevasse break was usually catastrophic, it continued to enlarge during the first 5-15 years.

108. In contrast to the moderate to poor correlation between river discharge and periods of growth in Mississippi River subdeltas, the Atchafalaya River deltas show good correlation during the first 8 years of subaerial growth, beginning in 1973. Rapid growth during the first 3 years was a result of large floods on the Mississippi River in 1973, 1974, and 1975. Growth slowed during the low flood year 1976-1977, then reversed for the next 2 years, when peak discharge was well below the long-term average (Figure 4). Renewed growth during the spring of 1979 can be correlated with the major flood of that year; and finally, the loss of subaerial land during the 1980-1981 flood year, slightly higher than expected, occurred during a year of average peak discharge.

109. The loss of subaerial land during 3 of the first 8 years has not resulted in a loss of total deltaic sediments. In fact, if the total volume of sediment is considered, the Atchafalaya River deltas have been steadily growing since at least 1967 and probably since 1952. Estimates of volume fill made from CE bathymetric and topographic survey sheets show that 140.1×10^6 m^3 of sediment were deposited between 1967 and 1977, at an average rate of 14.0×10^6 m^3 per year. Excluding subaerial land, this value can be further broken down to reveal that 19.7×10^6 m^3 were deposited between 1967 and 1972, 68.1 between 1972 and 1976, and 4.4 between 1976 and 1977 (data courtesy of R. H. Baumann). Thus even though subaerial sediments are lost (e.g., between 1976 and 1977), the subaqueous environment continues to grow.

110. Subaerial land is lost primarily during the winter months by waves and high water levels associated with the passage of cold fronts (van Heerden and Roberts 1980a and 1980b). Winds ahead of an approaching cold front are generally from the south and produce a setup in the bay that may exceed 1 m. As the front passes and winds become northerly, water is forced rapidly out of the bay, causing redistribution of sediment, especially from bars that lack the protection of a thick vegetative cover. Much of the eroded sediment resides in the shallow subaqueous environment and provides a base for future subaerial progradation.

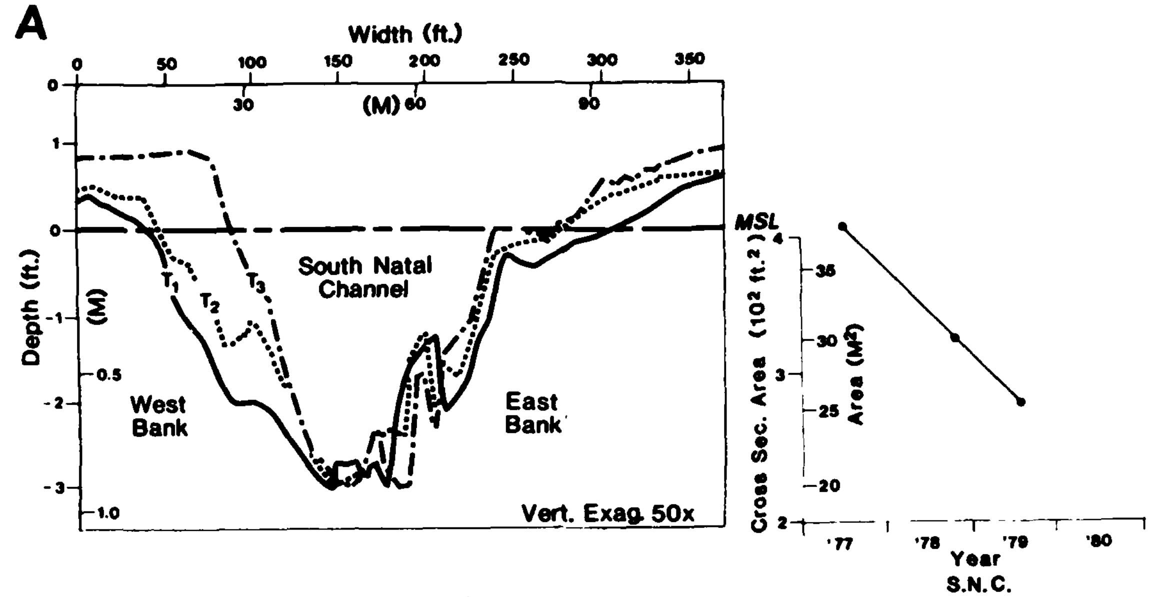
Channel Extension and Bifurcation

111. The fundamental mechanism by which the deltas in Atchafalaya Bay will continue to grow is by channel extension and channel bifurcation. Branching distributaries that are separated by complex delta lobes are characteristic of deltas which are frictionally dominated at the distributary mouths and are building into unstratified, low-energy, shallow-water environments (Welder 1959). High rates of channel extension in these deltas require that the system be dominated by fluvial processes rather than marine processes. As channels extend into the bay they are confined by their own natural levee deposits of silt and clay. With increasing channel length, slope of the energy gradient will decrease and aggradation, splitting, or diversion of flow to new branches will be favored.

112. Channel extension leads to subaerial growth by two processes: (a) accretion of the subaqueous natural levees and (b) formation of midchannel bars, which grow vertically. Figure 33 shows examples from the Lower Atchafalaya River Delta of these processes in operation during a 2-year period. Lateral and vertical growth of subaqueous natural levees (Figure 33A) not only adds new land to the delta lobes, but reduces the cross-sectional area of channels. This result is a tendency for channels to seal and lobes to fuse. The formation of midchannel bars that grow laterally and vertically also reduces channel cross sections and forms bridges between adjacent delta lobes. The dramatic growth of the midchannel bar in Southeast Pass attests to the importance of this process (Figure 33B).

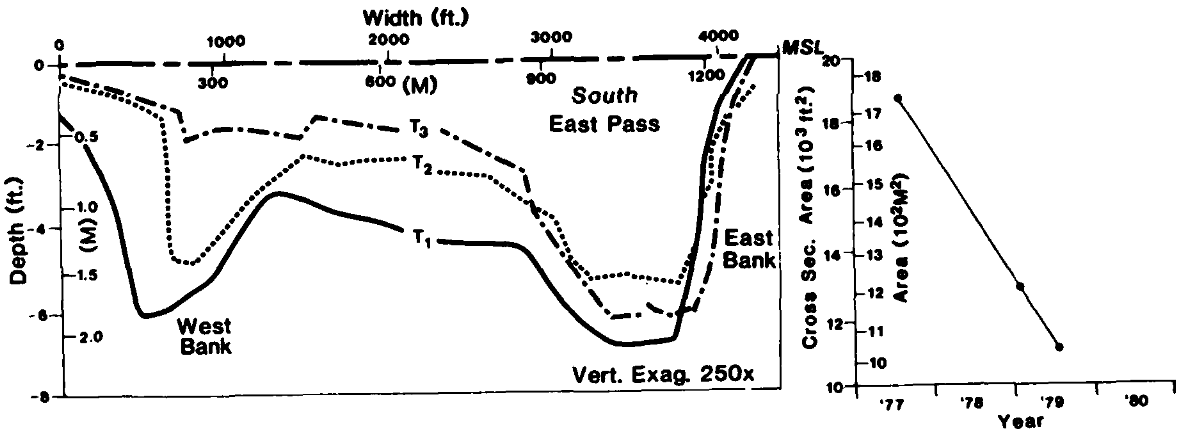
113. The formation of a midchannel bar is usually attributed to deposition of coarser particles as a result of either spreading of flow upon reaching an unconfined area or the establishment of an equilibrium between channel-building processes and prevailing winds and tide (Axelsson 1967). The deposition of coarse particles occurs when the distributary can no longer support its high sediment load under conditions of waning velocity and turbulence. The midchannel or distributary mouth bars create an obstruction to flow that, in turn, causes

A



PROFILE	DATE	CROSS-SECTIONAL AREA. ft^2 (m^2)
T1	JUN'77	395.9 (36.78)
T2	FEB'79	320.3 (29.76)
T3	JUL'79	276.7 (25.71)

B



PROFILE	DATE	CROSS-SECTIONAL AREA ft^2 (m^2)
T1	AUG'77	18,732.4 (1,740.30)
T2	JAN'79	12,936.5 (1,201.84)
T3	JUL'79	10,870.3 (1,009.86)

Figure 33. Time-history of channel sealing and lobe growth in the eastern half of the Lower Atchafalaya River Delta, 1977-1980. Channels seal by lateral and vertical extension of channel flanks and natural levees (A) and by development of a midchannel bar (B). (Figure courtesy of I. Ll. van Heerden)

the flow to bifurcate. Ordinarily, channels must continuously cut through their bar deposits in order to maintain discharge. However, small channels are less efficient than large channels and once initiated, the process of bifurcation will repeat itself. During flood stage sufficient sediment may be deposited on midchannel bars to give subaerial exposure at mean sea level.

114. The rate of channel extension over the life of the Mississippi River subdeltas averaged 180 m/yr. Maximum rates of 380-760 m/yr always occurred early in the life cycle; as the subdeltas began to lose subaerial land, the decrease in linear growth rate was a result of each distributary's having to fill a greater volume with sediment in order to move a unit distance horizontally. As channels grow and bifurcate, individual lobes begin to reach both farther upstream and farther downstream. Eventually, channels will seal and lobes will coalesce. Large lobes in the Atchafalaya River deltas are the result of the coalescence of numerous small distributary mouth bars.

115. Figure 34 shows the pattern of growth in the most active part of the eastern half of the Lower Atchafalaya River Delta between 1973 and 1979. The sediment delivery network has been selectively eliminated as a result of the processes described above. Because frictional resistance per unit volume of flow increases with decreasing channel size (Axelsson 1967), much of the area shown in Figure 34 is now reminiscent of a system that is on the verge of deterioration. Closing of channels, the final step in the channel extension process, effectively prevents nourishment of the delta except by overbank flooding at high river stage.

Future Development of Atchafalaya River Deltas

116. The future growth rates and subaerial configuration of the deltas in Atchafalaya Bay are obviously somewhat speculative. The main difficulties in projecting to the future are (a) uncertainty as to what modifications to the system will be made by man, (b) uncertainty as to the magnitude of spring floods, hence sediment discharge, during the

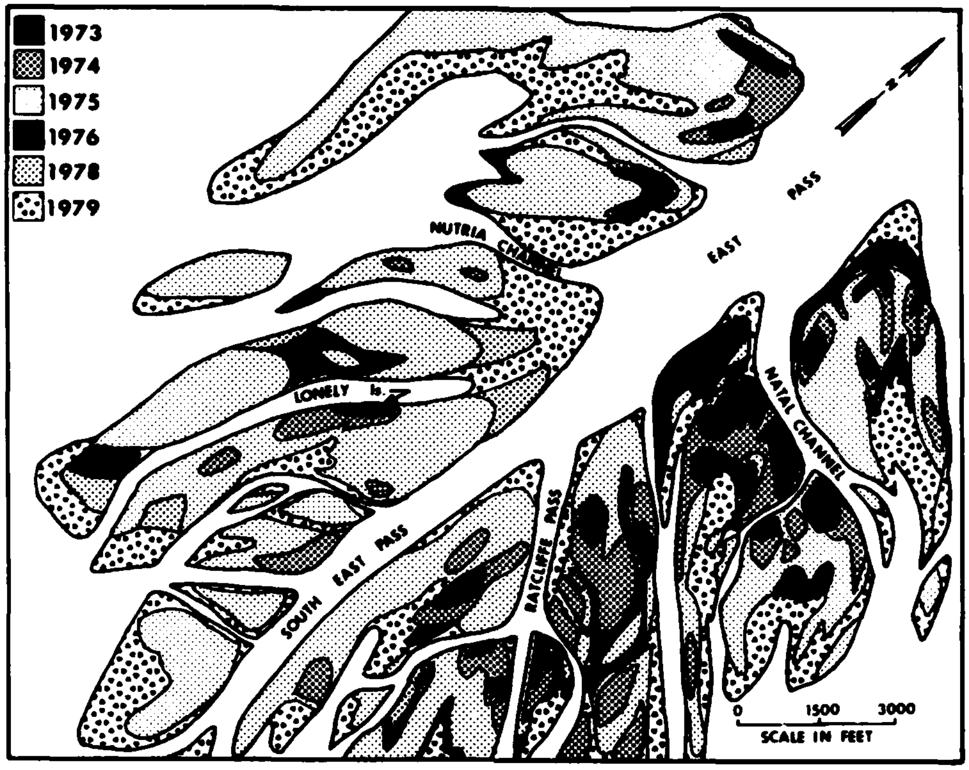


Figure 34. Progressive growth of delta lobes between 1973 and 1979 showing upstream and downstream extension, lobe fusion, and sealing of channels. (Figure courtesy of I. Ll. van Heerden)

next 50 years, and (c) the certainty that the Atchafalaya River deltas will not grow at precisely the same rate and in precisely the same fashion as any single delta examined as part of the generic analysis. These difficulties have been largely overcome by (a) assuming that man will not modify the system between 1980 and 2030, (b) projecting into the future for more than one discharge scenario, and (c) using information from four deltas (Mississippi River subdeltas) rather than one delta as a model for future growth in Atchafalaya Bay.

117. Prior to the generic analysis, several projections had been presented in the literature. They ranged from an extreme rate of subaerial growth of 14.2-16.9 km^2/yr, filling the bay before 1990 and leading to over 900 km^2 of subaerial land by 2020 (Shlemon (1972) citing

data from Garrett, Hawxhurst, and Miller 1969),* to more conservative estimates that lead to filling of the bay by the turn of the century (Roberts, Adams, and Cunningham 1980), to estimates that indicated the bay should fill to within 0.6 m of mean sea level (except channels) in a period of 60 years under normal flood regimes (Adams and Baumann 1980). The rates presented in the following paragraphs are the first to be determined using a generic model approach.

118. The Mississippi River subdeltas were selected as "the model" because of their similarity to the Atchafalaya River Delta and because of the excellent data base provided by maps and charts. The first step involved carrying out the following procedures:

- a. The four subdelta curves in Figure 27 were replotted to give time versus percentage of total growth normalized to 100 percent.
- b. Each curve was smoothed using a cubic regression best-fit line of the form $y = a + bx + cx^2 + dx^3$ (Table 4).
- c. The curves were renormalized to again adjust the percentage of total growth (Y-axis) to reach a peak at the 100 percent value.
- d. A common origin was established by changing the X-axis to represent the number of years after the first subaerial land, thus forcing each curve to begin at the new origin.

119. The results of procedures a-d are plotted in Figure 35. These normalized and smoothed curves show that the four Mississippi River subdeltas have remarkably similar histories; in particular, the rates of growth are nearly identical and the total number of years of growth (average 66 years) can all be bracketed within a period of 20 years.**

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* Infilling projections by Garrett, Hawxhurst, and Miller (1969) were made for the -2 ft contour (National Geodetic Vertical Datum) and therefore are not directly comparable to projections referenced to mean sea level.

** West Bay subdelta differs slightly in that it is the largest subdelta with the highest average and maximum rates of subaerial growth.

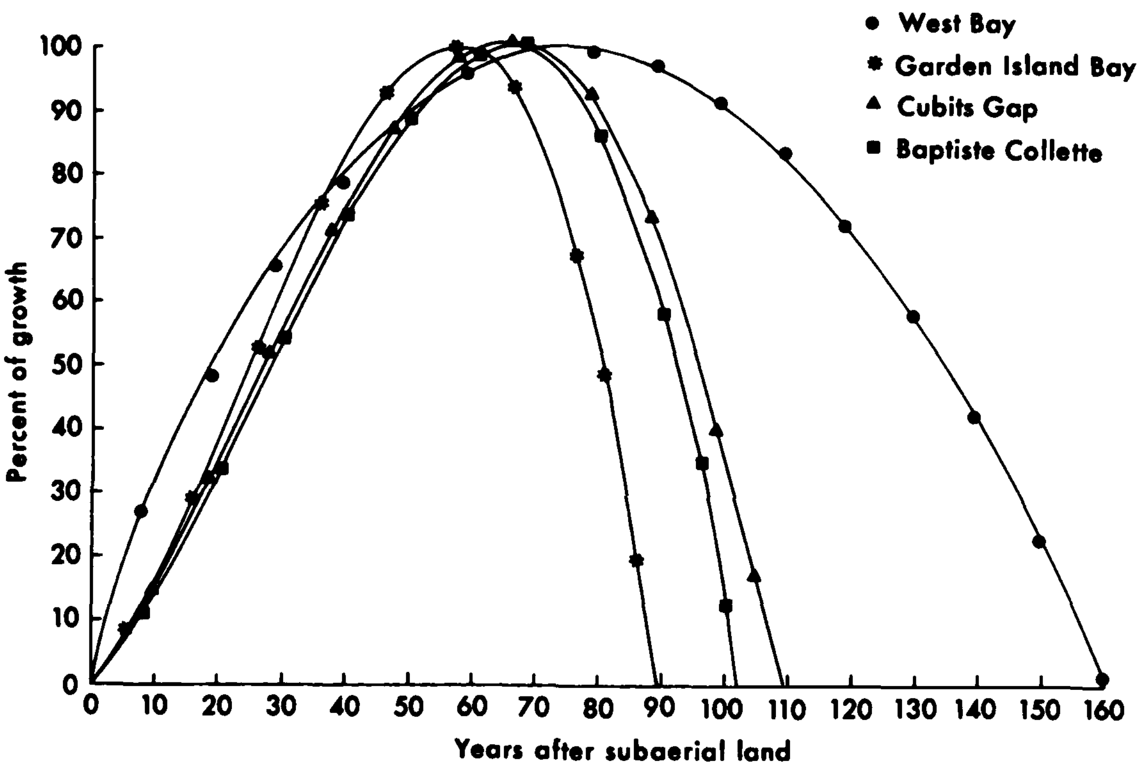

Figure 35. Normalized and smoothed curves showing growth and deterioration of the four Mississippi River subdeltas. Coefficients used in the cubic regression are given in Table 4

120. The next step was to determine for 5-year intervals beginning in 1980 the average percentage of total growth expected, on the basis of the Mississippi River subdeltas (subaerial land), and to project this to the year 2030. Then, by extrapolating from the amount of subaerial land in Atchafalaya Bay in the 1980 base year, the total amount of subaerial land could be projected to any year in the future using the nondimensionalized growth curves in Figure 35 (Table 5). Using the three estimates for total subaerial land in Atchafalaya Bay, as discussed in paragraph 91, upper and lower growth curves were constructed (Figure 36). The maximum amount of land in Atchafalaya Bay in 2030 was achieved using the least squares estimate for the 1980 base year; the minimum amount of land was produced using the 1980 observed value. Assuming the Mississippi River subdeltas to be a reasonable model, the total subaerial land in the year 2030 would be bracketed by the values 150 km^2 and 208 km^2.

121. The final step was to plot on a base map the configuration of land in 2030, based on several different rates of growth (Figure 37). The upper and lower bounds from Figure 36 were selected for two of these, and the third, an extreme bound, was taken to be the amount of land produced at a growth rate for 50 years equal to the maximum during the first 8 years (6.73 km^2/yr). Including this extreme bound of 337 km^2, the expected amount of land in Atchafalaya Bay could vary slightly more than twofold, depending on the selected rate of growth.

122. Construction of the actual configuration of subaerial land was guided by the following criteria:

a. The bathymetry of the bay, insofar as known, was used to determine which areas were most likely and which were least likely to be filled. In particular, deep holes and persistent scour channels were left as the last areas to become subaerial land.

b. Patterns in the previous 8 years of subaerial growth and 30 years of subaqueous growth were used as a means of extending the delta front toward the shell reefs.

c. Knowledge gained from examining historic maps, charts, and aerial photographs of similar lobate deltas was used as much as possible. The primary principles applied

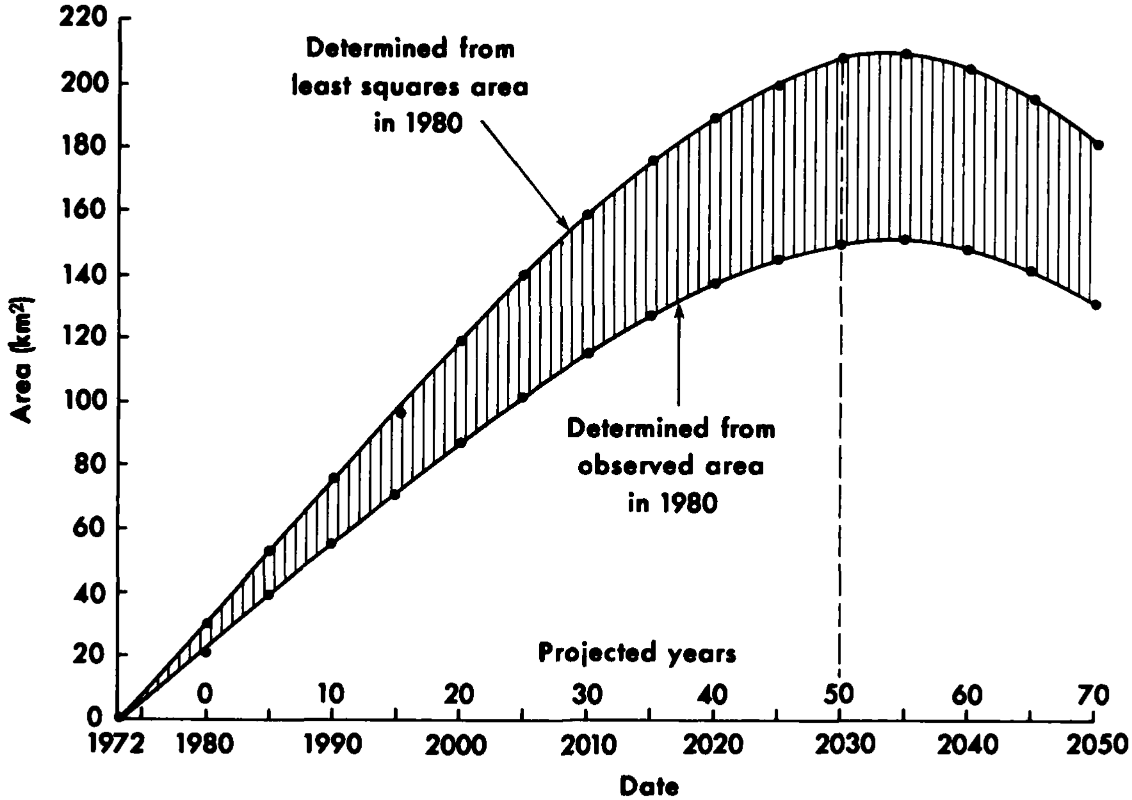

Figure 36. Growth curves predicting subaerial land in Atchafalaya Bay in the year 2030. Determinations made from growth curves of Mississippi River subdeltas assuming 28.8 km^2 of land (upper curve) and 20.8 km^2 of land (lower curve)in Atchafalaya Bay in 1980

were channel extension, channel bifurcation, and lobe fusion.

d. The subaerial delta front was constructed to resemble that of a shallow lobate delta but must be considered as somewhat idealized since such projections are beyond the realm of a generic analysis.

123. Several features of the above projections are noteworthy. First, the Atchafalaya Bay will not fill by the year 2030 but will retain large open areas 1-2 m deep. Second, even though the bay will remain partially open, subaerial land will extend onto the shelf and begin building a true marine delta. Third, four channels, numbered 1-4 in Figure 37, will not seal within 50 years and will continue to carry water and sediment into the large delta lobes. Fourth, the area

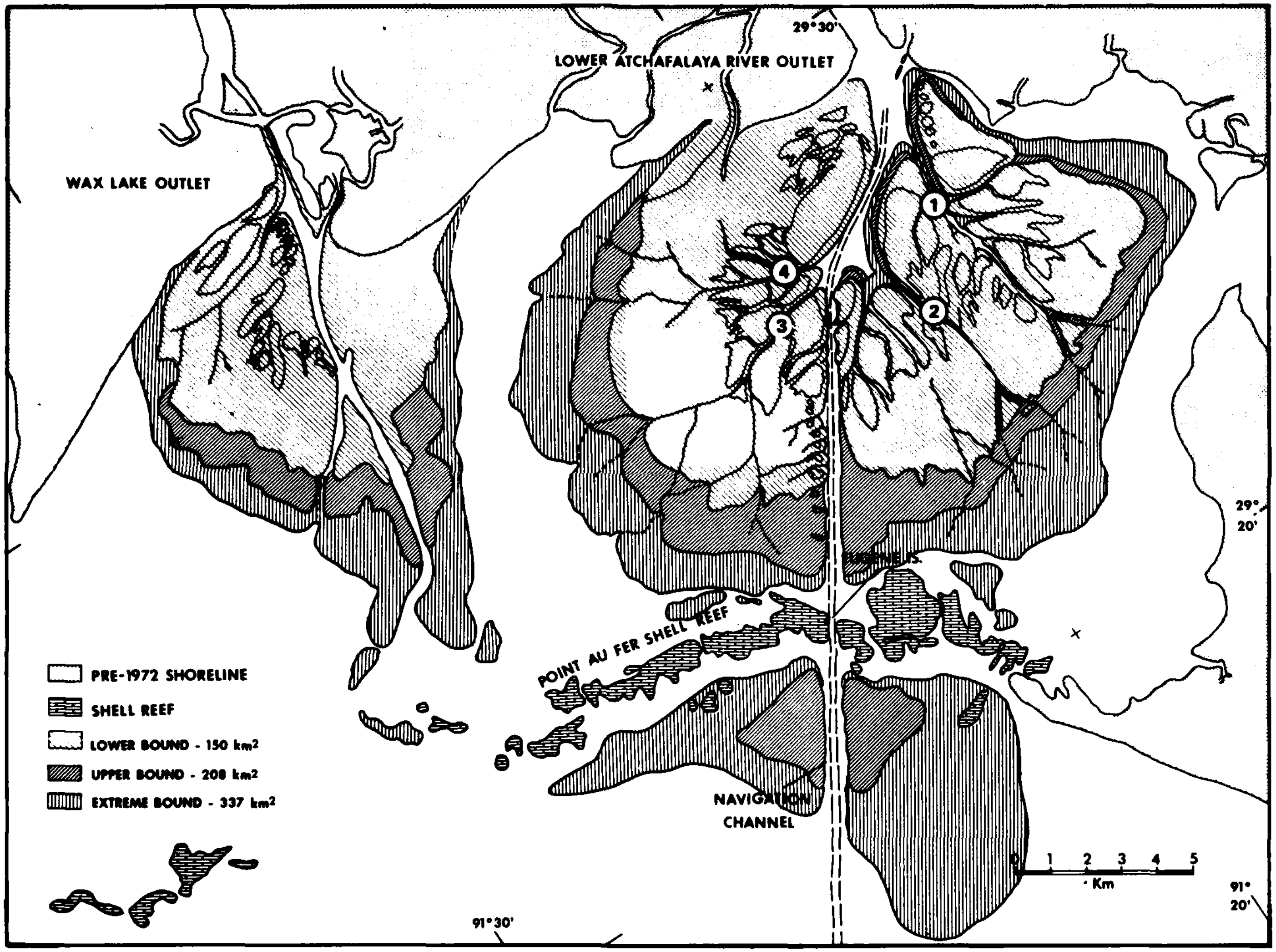

Figure 37. Configuration of subaerial land in Atchafalaya Bay in the year 2030 assuming total areas of 150 km^2, 208 km^2, and 337 km^2

surrounding the shell reefs will not fill with sediments and will remain as the deepest areas in the bay. Fifth, the Wax Lake Delta in 50 years will represent more than the 10-17 percent of total area that it now represents.

124. Complete filling of the bay is unlikely to occur within 50 years because of several major scour channels; even without widespread scour, the volume of incoming sediments would be insufficient to produce a continuous cover of subaerial land. A major scour channel 2-3 m deep between the entrance to Four League Bay and Point au Fer will be one of the last parts of the bay to be filled (Figure 37). Because of this channel, the embayment to the southeast will receive very little sediment from the advancing delta front. The embayment in the far northeast part of the bay will also remain open, since little sediment is transported north of the advancing delta front. Sediment samples taken in 1980-1981 indicated that both of these embayments were covered by only a few centimetres of prodelta clays overlying the old bay-bottom sediment (Coastal Studies Institute, LSU, unpublished data).

125. A second scour channel between the Lower Atchafalaya River Delta and the Wax Lake Delta will probably remain open, thus preventing the two deltas from merging during the next 50 years unless fused by overwhelming quantities of sediment from an exceptionally large flood. Deep holes and channels, both natural and dredged, occur throughout the Point au Fer shell reefs and serve as conduits for the transport of water between the bay and the continental shelf. Strong currents, isolated scour, and the overall water depth will prevent new land from forming along this line of shell reefs. East Pass, Poulledieux Channel, Log Channel, and Amerada Hess Channel, indicated in Figure 37 by the numbers 1-4, respectively, are the four strongest channels in the Lower Atchafalaya River Delta and will not seal naturally. Sustained currents of 50-100 cm/sec are recorded regularly in these channels (Coastal Studies Institute, LSU, unpublished data).

126. Growth of the Wax Lake Delta will continue at a faster rate than the Lower Atchafalaya River Delta, resulting in an area after 50 years that is approximately 25 percent of the total land area in

Atchafalaya Bay. In 1980, Wax Lake achieved a sediment-filled state similar to that in Grand and Six Mile Lakes, and caused accelerated growth in the Wax Lake Delta. Examination of LANDSAT images at low water levels shows extensive areas of subaqueous sediment only 10-30 cm below mean sea level near the Wax Lake navigation channel (I. Ll. van Heerden, personal communication).

Extension to the shelf

127. Extrapolation of the deltas beyond the Point au Fer shell reefs is particularly difficult because of the added influence of marine processes. However, two of the predictions, the upper bound and the extreme bound, indicate that land will be emerging on the shelf by 2030 (Figure 37). The sediments in these delta lobes will be subject to reworking by waves, and quite possibly currents will produce a size fractionation in the sediment while at the same time skewing the delta lobes unexpectedly to the southeast. Although silt- and clay-sized sediments are and will continue to be carried to the west in the Atchafalaya mud stream (Wells and Kemp, 1981), the strongest currents during the year occur immediately after the passage of cold fronts. Adams, Wells, and Coleman (1982) have shown from the analysis of current records that these wind-driven currents are directed to the southeast and, further, that they are the only currents strong enough to transport fine sands. The result will be a tendency to skew the sandy delta lobes to the southeast, thereby fractionating sands from the mean drift of muddy sediments to the west.*

128. As subaerial land emerges on the shelf, some deterioration of the delta within the bay can be expected. In particular, as the eastern half of the Lower Atchafalaya River Delta fills, the system for delivering sediment will become more inefficient and numerous small channels will seal. Examination of aerial photographs shows that after only 8 years of subaerial growth many small channels have already sealed and lobe fusion is an extremely active process. Continuous subsidence at a rate of, say, 1 cm/yr will allow, in the absence of sediment input,

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* This hypothesis does not consider the possibility that waves can suspend sand for movement by weak subcritical currents.

localized deterioration processes to begin. Further, sediments will always be removed by water exchange between the bay and open shelf as a result of tidal currents, waves, and setup and setdown during cold-front passage.

129. When Atchafalaya Bay reaches its sediment-filled state, that is, has acquired as much sediment as it can accommodate, then progradation on the shelf should accelerate. Just as Atchafalaya Bay began to fill rapidly when Grand and Six Mile Lakes became sediment-filled, the offshore areas will begin to grow rapidly when the bay is essentially filled with sediment. Part of the sediment that enters the shelf environment will continue to be carried west to the chenier plain, reversing the present trend of coastal erosion in these downdrift areas.

Selection of a growth rate

130. With respect to subaerial growth projected by the subdeltas model, the upper bound of 208 km^2 is considered to be the most reasonable estimate under normal flood conditions. This figure, based on an initial amount of land determined by the least squares method, is the only estimate of total land that includes all data taken during the first 8 years of delta growth. Although the 1970's decade was one of abnormally high spring floods, any additional land built by these floods would not be considered to bias the projections upward since the LANDSAT analysis typically underestimates actual subaerial land by 10-15 percent. An important point to note is that the Mississippi River subdeltas model is valid, even if the time scale is changed to reflect a more reasonable life cycle of 600-800 years for the Atchafalaya River deltas. That is, the projection for total subaerial land after 50 years on a 600-year life cycle is very close to that on a 150-year life cycle, provided the subdelta growth curve has the same shape and is nondimensionalized to represent percentage of total growth.* Thus,

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* For example, Table 5 indicates that for a 150-year cycle 28.8 km^2 of land represents 13.6 percent of total area, which after 50 years becomes 207.5 km^2. On a 600-year cycle, 28.8 km^2 of land would represent approximately 1.8 percent of total area, which after 50 years would become 200.0 km^2.

even though the Mississippi Delta is a mature delta that is deteriorating and the Atchafalaya deltas are young and rapidly prograding, comparisons between the two are not unreasonable. Further, it is important to reemphasize in this regard that within any delta system, growth and deterioration can occur simultaneously. Selection of an overall growth rate does not preclude the center of deposition from shifting several times throughout the life history of the Atchafalaya deltas.

131. Although the prediction of 208 km^2 of subaerial land by 2030 is considerably lower than those reported previously, several lines of evidence indicate that this value should nevertheless be considered quite reasonable.

a. A total subaerial growth of 208 km^2 over a period of 50 years can be achieved at an average growth rate of 4.2 km^2/yr, a value approximately 2-4 times higher than the average for the Mississippi River subdeltas, 25 times higher than the maximum growth rate for the Trinity Delta, 2 times higher than the maximum growth rate for the Colorado Delta, and equal to the maximum growth rate of the Danube Delta. Thus none of the lobate deltas examined in this analysis, regardless of river discharge or depth of receiving basin, has grown at an average rate exceeding 4.2 km^2/yr.

b. The maximum rate of growth in the Atchafalaya Bay was 6.73 km^2/yr, a value essentially the same as the maximum rate of growth in the Cubits Gap, West Bay, and Garden Island Bay subdeltas (Table 3). Figures 21, 23, and 25 show that within 30 years of birth (age of Atchafalaya River deltas), each of these subdeltas had reached its maximum rate of growth. None of the subdeltas sustained its maximum rate for 50 years; the average period of maximum growth was 17.3 years. Thus the extreme bound of 337 km^2, produced at a rate of 6.73 km^2/yr, should be considered the amount of subaerial land produced during five decades of discharge similar to that of the 1970's decade.

c. The fact that Atchafalaya River discharge is more than twice that of any Mississippi River subdelta is unimportant when the rate of volume fill is considered. At an average rate of 14 x 10^6 m^3/yr, the Atchafalaya Bay is filling at a rate consistent with the Mississippi River subdeltas (Baptiste Collette = 9 x 10^6 m^3/yr; Cubits Gap = 26 x 10^6 m^3/yr; West Bay = 19 x 10^6 m^3/yr; Garden Island Bay = 4 x 10^6 m^3/yr). Because of the large, well-defined navigation channel, the percentage of sediment retained in Atchafalaya Bay is relatively low, thus leading to a growth rate close to that of the two largest subdeltas (Cubits Gap and West Bay). Finally, assuming an average depth of 2 m and a rate of fill of 14×10^6 m^3/yr, the open bay (520 km^2 in 1980) would take 74 years to fill, generally supporting the calculations for subaerial growth.

PART V: CONCLUSIONS

132. Results of the generic analysis support the following major conclusions on past, present, and future growth of deltas in Atchafalaya Bay:

a. Subaerial land in Atchafalaya Bay is growing at a rate of 3.6 km^2/yr and is expected to reach the open shelf within 50 years. Although growth has been episodic, major floods correlate well with high growth rates, and lower than average discharges result in the loss of subaerial land.

b. At mean sea level, 10-17 percent of total subaerial land occurs in the Wax Lake Delta and 83-90 percent occurs in the Lower Atchafalaya River Delta. Within the Lower Atchafalaya River Delta, 70 percent of the subaerial land is west of the navigation channel. The rate of growth in the Wax Lake Delta will increase relative to that in the Lower Atchafalaya River Delta, and by 2030 the Wax Lake Delta will represent approximately 25 percent of total land area.

c. Projected rates of growth based on subdeltas of the modern Mississippi River Delta indicate that total subaerial land in Atchafalaya Bay will range from 150 km^2 to 337 km^2 in the year 2030. The most reasonable estimate under conditions of normal discharges is 208 km^2, with 150 km^2 and 337 km^2 representing 50 years of lower than average and substantially higher than average discharges, respectively.

d. Subaerial land will emerge on the open shelf well before the bay reaches a sediment-filled condition. It is therefore inappropriate to consider the formation of a marine delta only as a followup to development of a continuous land mass in Atchafalaya Bay. In fact, Atchafalaya Bay will probably never reach a completely sediment-filled state as a result of scour channels, very slow sedimentation in distal areas, reworking of sediments during the passage of cold fronts, subsidence, and selective natural sealing of the sediment delivery network.

e. The subaerial deltas will continue to grow as lobate features by the processes of channel extension, channel bifurcation, and lobe fusion. Within 50 years, the hundreds of small lobes will have fused into perhaps 10 major lobes separated by small dying channels. Four main arteries will continue to deliver sediment: Natal Channel and Poulledieux Channel, on the east side of the navigation channel; and Log Channel and Amerada Hess Channel, on the west side of the navigation channel.

f. The Atchafalaya Bay retains approximately 14×10^6 m^3 of sediment per year, an amount equal to that retained, on average, in the four Mississippi River subdeltas. Subaerial land eroded during the passage of cold fronts resides in the shallow subaqueous environment and provides a platform for future progradation. The low ratio between sediment retention and river discharge may be attributed to the efficiency of the navigation channel in transporting sand-sized particles through the bay to the continental shelf, although the quantity transported is still speculative.

g. Volumetric computations further indicate that Atchafalaya Bay is filling at a rate consistent with that of the Mississippi River subdeltas (range 4-26 $\times 10^6$ m^3 of sediment per year). With an average depth of 2 m and a rate of fill of 14×10^6 m^3/yr, the open bay (520 km^2 in 1980) will take 74 years to fill.

h. Waves and wind-driven currents will become more important in shaping the delta lobes as they prograde onto the continental shelf. Strong southeasterly currents following the passage of cold fronts may tend to skew the sandy components to the southeast, thus fractionating them from the silts and clays that will be carried west in the predominant drift system. The downdrift recipient of Atchafalaya River sediments, the Louisiana chenier plain, will undergo a dramatic reversal in its present trend toward coastal erosion during the next 50 years.

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Table 1

Process Variables for Deltas Examined as Part of Generic Analysis

Delta	Climate	River Discharge 10^3 m^3/sec	Sediment Type	Wave Power 10^7 ergs/sec	Tide Range m	Alongshore Current cm/sec	Shelf Slope %	Tectonics*
Mississippi Subdeltas								
Baptiste Collette	HST	0.608	HSL**	0.021	0.5	<10	0.03	2-4
Cubits Gap	HST	2.262	HSL	0.071	0.5	<10	0.07	2-4
Garden Island Bay	HST	0.640	HSL	0.044	0.5	<10	0.05	2-4
West Bay	HST	0.750	HSL	0.126	0.5	<10	0.03	2-4
East Texas Deltas								
Colorado	DST	0.124	HSL	Low†	0.5	Extremely low††	0.05	0.5
Trinity	HST	0.222	HSL	Low	0.5	Extremely low	0.01	1.0
Guadalupe	DST	0.046	HSL	Low	0.4	Extremely low	0.01	0.3
Foreign Deltas								
Danube	HTE	6.250	HSL	0.034	0.0	<10	14.1+	<0.05
Laitaure	HSA	0.025	HBL++ (14%)	Extremely low	0.0	0	1.0+	<0.05
Catatumbo	HT	0.944	HSL	Low	0.1	<10	0.5+	0.01
Atchafalaya River Deltas	HST	5.126	HSL	Low	0.5	Extremely low	0.01	1.3

Note: Values represent average conditions. Sources of data were as follows: climate, river discharge, sediment types, and alongshore currents were obtained from publications on individual deltas as cited in text; wave power obtained primarily from Coleman and Wright (1975) and Becker (1972); tide range obtained from

(Continued)

Table 1 (Concluded)

NOAA Tide Tables and publications cited in text; shelf slope measured from maps and charts; and tectonics (subsidence and sea level rise) obtained from Hicks and Crosby (1974), Swanson and Thurlow (1973), and publications cited in text.

HST = humid subtropical; DST = dry subtropical; HTE = humid temperate; HSA = humid subarctic; HT = humid tropical; HSL = high suspended load; HBL = high bed load.

*Subsidence and sea level rise in centimetres per year.
**High suspended load defined as greater than 95 percent.

†Low wave energy defined as less than 1.0 x 10^7 ergs/sec.
††Extremely low alongshore current defined as 0-5 cm/sec.
‡Represents the slope of delta front (receiving basin data unavailable).

Table 2

Subjective Evaluation of Similarity Between Lower Atchafalaya River Delta and Deltas Used in the Generic Analysis

Delta	Climate	River Discharge	Sediment Type	Wave Power	Tide Range	Alongshore Current	Shelf Slope	Tectonics	Average Similarity
Mississippi Subdeltas									
Baptiste Collette	1	1	1	1	1	2	1	2	1.25
Cubits Gap	1	1	1	3	1	3	3	2	1.88
Garden Island Bay	1	1	1	3	1	3	2	2	1.75
West Bay	1	1	1	3	1	3	2	2	1.75
East Texas Deltas									
Colorado	2	2	2	1	1	1	1	1	1.38
Trinity	1	2	2	2	1	2	1	1	1.50
Guadalupe	2	2	2	1	1	1	1	1	1.38
Foreign Deltas									
Danube	2	2	2	1	3	2	1	3	2.00
Laitaure	3	2	3	3	3	2	2	3	2.63
Catatumbo	2	2	2	2	3	2	2	3	2.25

Note: 1 = alike, 2 = similar, 3 = different.

AD-A140 446 THE ATCHAFALAYA RIVER DELTA REPORT 4 GENERIC ANALYSIS OF DELTA DEVELOPMEN..(U) LOUISIANA STATE UNIV BATON ROUGE COASTAL STUDIES INST J T WELLS ET AL. JAN 84 2/2

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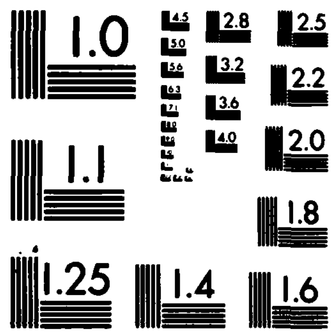

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Table 3

Summary of Growth and Deterioration in the Mississippi River Subdeltas

Characteristics		Baptiste Collette	Cubits Gap	West Bay	Garden Island Bay
		Subdelta			
Date of Crevasse		1874	1862	1839	1891
Duration of Life Cycle (Years)	Expected	125	135	175	115
	Remaining	19	17	34	26
Discharge Gradient* (m/km)	Initial	1.5	9.0	6.1	7.5
	1959	0.1	0.05	0.05	0.06
Percent of Total Discharge**	(1949-1974)	3.9	14.5	4.8	4.1
	1972	4.5	10.7	6.3	Not gaged
Maximum Subaerial Extent (km^2)		57	193	297	104
(Date)		(1946)	(1946)	(1932)	(1922)
Maximum Linear Extent (km)		12.9	19.3	22.2	12.8
(Date)		(1959)	(1971)	(1922)	(1953)
Maximum Volume (km^3)		0.75	3.50	3.30	0.95
(Date)		(1971)	(1971)	(1971)	(1971)
Subaerial Growth Rate (km^2/yr)	Maximum	1.1	6.3	7.0	6.9
	(Period)	(1891-1908)	(1891-1905)	(1845-1875)	(1914-1922)
	Average	0.8	2.2	2.7	2.5
	(Period)	(1874-1946)	(1862-1946)	(1845-1932)	(1891-1922)
Rate of Deterioration (km^2/yr)	Maximum	1.8	12.9	7.0	2.5
	(Period)	(1958-1971)	(1946-1952)	(1958-1971)	(1946-1953)
	Average	1.0	4.1	4.1	1.1
	(Period)	(1946-1971)	(1946-1971)	(1932-1971)	(1922-1971)

(Continued)

* Data from Morgan (1977)

** Data from U.S. Army Corps of Engineers, 1949-1974. Garden Island Bay based on a single gaging.

Table 3 (Concluded)

Characteristics		Baptiste Collette	Cubits Gap	West Bay	Garden Island Bay
		Subdelta			
Volume Growth Rate (km^3/yr)	Maximum	0.013	0.045	0.044	0.004
	(Period)	(1946-1971)	(1877-1905)	(1946-1971)	(1922-1971)
	Average	0.009	0.026	0.019	0.004
	(Period)	(1891-1971)	(1877-1971)	(1845-1971)	(1891-1971)
Linear Growth Rate (km/yr)	Maximum	0.38	0.61	0.76	0.42
	(Period)	(1915-1922)	(1905-1922)	(1859-1875)	(1891-1914)
	Average	0.15	0.20	0.17	0.20
	(Period)	(1874-1959)	(1874-1971)	(1845-1971)	(1891-1953)

Table 4

Coefficients Used in Cubic Regression Analysis of Mississippi River Subdeltas

Procedure	Baptiste Collette	Cubits Gap	West Bay	Garden Island Bay
a	-4.8004	-11.2219	3.8152	-3.3499
b	0.0541	0.5786	2.4472	0.6674
c	0.0527	0.0326	-0.0174	0.0602
d	-0.0472×10^{-2}	-0.0310×10^{-2}	0.0013×10^{-2}	-0.0714×10^{-2}

Table 5

Predicted Subaerial Land in Atchafalaya Bay Based on Growth Rates of Mississippi River Subdeltas

Date	Years After Subaerial Land	Projected Years	Percent of Total Area	Total Subaerial Land Least Squares	Total Subaerial Land Observed	Total Subaerial Land Average
1972	0		0	0	0	0
1980	8	0	13.6	28.8	20.8	21.5
1985	13	5	25.0	52.9	38.2	39.5
1990	18	10	35.8	75.8	54.8	56.6
1995	23	15	45.0	95.3	68.8	71.4
2000	28	20	56.3	119.2	86.1	89.0
2005	33	25	65.8	139.3	100.6	104.0
2010	38	30	74.5	157.8	113.9	117.8
2015	43	35	82.3	174.3	125.9	130.1
2020	48	40	89.0	188.5	136.1	140.7
2025	53	45	94.3	199.7	144.2	149.1
2030	58	50	98.0	207.5	149.9	154.9
2035	63	55	98.5	208.6	150.7	155.7
2040	68	60	96.8	204.9	148.1	153.0
2045	73	65	91.8	194.4	140.4	145.1
2050	78	70	85.5	181.1	130.8	135.2

Note: Existing subaerial land in Atchafalaya Bay in 1980 was determined by least squares interpolation, observed values, and average values for 1975-1980.

APPENDIX A: MAPS DIGITIZED FOR GENERIC ANALYSIS

Date*	Source	Identification Name or Number	Scale	Area of Interest
1817	Nat. Archives	Pouisson	1:61,000	WB
1838	Nat. Archives	Talcott	1:61,000	MD
1845	Nat. Archives	La Tourette	1:80,000	WB
1855	C and GS	Trinity Bay	1:24,000	TD
1875	Nat. Archives	Howell	1:80,000	WB
1885 (1877)	C and GS	194	1:80,000	CG
1885 (1884)	C and GS	194	1:80,000	MD
1886	C and GS	194	1:80,000	MD
1891	USGS 15'	East Delta, La.	1:62,500	CG, GIB
1891	USGS 15'	West Delta, La.	1:62,500	WB
1893 (1891)	USGS 15'	Fort, La.	1:62,500	WB, BC
1906 (1905)	C and GS	194	1:80,000	MD
1925 (1922)	C and GS	1272	1:80,000	MD
1928	Carib. Petro. Co.	Lake Maracaibo	1:20,300	CAD
1930	Carib. Petro. Co.	Lake Maracaibo	1:50,000	CAD
1933 (1932)	C and GS	1272	1:80,000	MD
1933	C and GS	Trinity Bay	1:24,000	TD
1935	USGS 15'	Garden Is. Pass 15' Quad	1:62,500	CG
1935	USGS 15'	W. Delta	1:62,500	CG, WB
1942	Army Map Service	Anahuac, Tx	1:25,000	TD
1949	Carib. Petro. Co.	Maracaibo Bar Survey	1:50,000	CAD
1956 (1946)	C and GS	1272	1:62,500	MD
1958	USGS	Breton Sound	1:62,500	CG
1958	COE 15'	East Delta, La. La. 15'	1:62,500	CG GIB

(Continued)

Appendix A (Concluded)

Date*	Source	Identification Name or Number	Scale	Area of Interest
1958	USGS 15'	West Bay, La.	1:62,500	CG, WB
1960 (1958)	USGS 15'	Venice, La.	1:62,500	CG, BC, WB
1961	USGS 7.5'	Anahuac, Tx	1:24,000	TD
1971	USGS 7.5'	Dixon Bay, La.	1:24,000	WB
1971	USGS 7.5'	GI Pass, La.	1:24,000	GIB
1971	USGS 7.5'	Pass a Loutre, East La.	1:24,000	CG, GIB
1971	USGS 7.5'	Pass a Loutre, West La.	1:24,000	CG, GIB
1971	USGS 7.5'	Pass du Bois, La.	1:24,000	WB
1971	USGS 7.5'	Pass Tante Phine	1:24,000	WB
1971	USGS 7.5'	South Pass, La.	1:24,000	GIB
1971	USGS 7.5'	Pilottown, La.	1:24,000	CG, WB
1971	USGS 7.5'	Triumph, La.	1:24,000	WB
1971	USGS 7.5'	Venice, La.	1:24,000	CG, BC, WB
1972 (1952)	USGS 7.5'	Matagorda, Tx	1:24,000	CD
1973 (1952)	USGS 7.5'	Austwell, Tx	1:24,000	GD
1974 (1961)	USGS 7.5'	Anahuac, Tx	1:24,000	TD
1975 (1856-1957)	Texas Bur. Econ. Geol.	Matagorda Bay	1:24,000	CD

CG - Cubits Gap
MD - Mississippi Delta
GIB - Garden Island Bay
AB - Atchafalaya Bay
BS - Baptiste Collette
WB - West Bay
TD - Trinity Delta
GD - Guadalupe Delta
CD - Colorado Delta
CAD - Catatumbo Delta

*Date of publication (date of survey, if different)

APPENDIX B: LANDSAT IMAGES USED TO CONSTRUCT ATCHAFALAYA DELTA GROWTH CURVES

			Exposed Area km^2	
Date	Microform No.	Water Level cm	Lower Atchafalaya River Outlet	Wax Lake Outlet
26 Sep 73	1100150947	-1.5	5.70	0.44
1 Nov 73	1100161528	19.8	10.54	0.11
19 Nov 73	1100180221	28.9	4.07	--
7 Dec 73	1100180838	-22.9	2.41	--
30 Jan 74	1100200912	32.0	2.90	0.01
17 Feb 74	1100201587	1.5(2.0)	4.64	0.64
30 Apr 74	1100240716	57.9	2.12	--
11 Jul 74	1100270099	33.5	3.55	0.12
4 Oct 74	1100310127	38.1	4.95	0.06
2 Dec 74	1100320688	-36.6	16.86	2.56
12 Feb 75	1100340355	1.5	7.67	0.70
2 Mar 75	1100350555	13.7	6.40	0.65
16 Apr 75	2100050111	42.7	3.94	--
24 Jul 75	1100400252	27.4	9.12	--
25 Sep 75	2100110218	6.1	16.21	0.90
31 Oct 75	2100120526	13.7	11.81	0.80
27 Nov 75	1100440199	-4.6	20.02	1.40
6 Dec 75	2100130700	-7.6(-13.0)	25.05	2.20
20 Jan 76	1100450660	-3.0	22.74	1.21
29 Jan 76	2100150057	-15.2	34.11	1.95
25 Feb 76	1100470152	-12.2	14.95	1.60
1 Apr 76	1100480314	18.9	11.61	0.51
10 Apr 76	2100171211	19.8	12.44	0.72
3 Jun 76	2100190512	37.5	8.02	--
12 Jun 76	1100500562	36.6	8.15	0.28

(Continued)

Appendix B (Continued)

Date	Microform No.	Water Level cm	Exposed Area km^2 Lower Atchafalaya River Outlet	Wax Lake Outlet
10 Feb 77	2100270477	(6.1)	--	1.49
28 Feb 77	2100280066	-7.9	36.95	2.50
18 Mar 77	2100281124	-7.9	34.72	2.50
5 Apr 77	2100290630	0.0	--	2.00
23 Apr 77	2100291291	12.0	--	1.15
11 May 77	2100300359	35.0	--	0.49
17 May 77	1100580332	26.0	--	1.00
29 May 77	2100310703	28.3	11.20	0.43
4 Jun 77	1100590246	32.0	--	0.50
22 Jun 77	1100600073	21.3	--	0.90
7 Nov 77	--	16.5	14.18	1.15
5 Feb 78	2900610725	-18.1	31.57	3.05
27 Apr 78	3900170899	20.7(18.3)	5.59	0.20
15 May 78	3900150845	16.5	5.12	--
17 Jul 78	2900720663	20.7(30.0)	6.81	1.18
4 Aug 78	2900770344	-1.5	13.62	1.62
24 Oct 78	3900460284	10.2(11.0)	9.86	1.05
2 Nov 78	2900810668	-6.6	27.30	3.00
11 Nov 78	3900470812	(-1.5)	--	1.64
17 Dec 78	3900530315	-9.0	25.70	3.00
26 Dec 78	--	4.0	15.98	1.36
22 Jan 79	--	6.0	11.03	1.10
9 Feb 79	7900010173	8.4	16.94	1.00
27 Feb 79	7900220169	13.5	19.98	--
8 Mar 79	7900160719	17.4	15.49	1.62

(Continued)

Appendix B (Concluded)

Date	Microform No.	Water Level cm	Exposed Area km^2 Lower Atchafalaya River Outlet	Exposed Area km^2 Wax Lake Outlet
17 Aug 79	7900160137	21.3	9.96	1.04
24 Nov 79	7900600061	-5.5	31.96	3.70
4 Feb 80	--	-8.7	33.78	4.22
4 Oct 80	7900360047	19.8	11.26	1.97
9 Nov 80	7900330332	-22.9	36.28	8.28
24 Mar 81	7900591028	-15.5	25.64	5.37

Note: All images were from Path 24, Row 40, of LANDSAT grid. Occasionally water level in the Wax Lake Outlet Delta differed from that in the Lower Atchafalaya River Delta; Wax Lake water levels are given in parentheses.

END

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